FROM DESIGN TO IMPLEMENTATION: INNOVATIVE SLOW SAND FILTRATION FOR USE IN DEVELOPING COUNTRIES

By

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Abstract

During January 2002, the author traveled to Nepal to evaluate the Biosand Filter Pilot Project, which introduced 12 innovative intermittently operated slow sand filters into homes and schools in 5 different villages of the Lumbini District. In addition, she assessed the microbial contamination of tubewells in 17 villages including those with Biosand filters, which are part of the International Buddhist Society (IBS) health outreach program. Constructed in the Nawalparasi District by Nepalese Durga Ale, Biosand filters and their media were transported to Lumbini villages where they were commissioned during the first week of January 2002. While technically sound procedures were followed for both filter construction and commissioning, the importance of protecting the biofilm and *schmutzdecke* did not seem to be understood. Filter owners expressed a desire to become more educated about their filters as basic filter operation and maintenance did not appear to be practiced. In addition, flow rates dropped sharply following installation, which suggests a problem with the sand source or sand preparation procedure.

Expanding the Lumbini Biosand Pilot Project offers an opportunity to refine the existing Biosand construction, distribution, and education process. Recommendations include improving sand preparation, involving the community in media sifting and washing, disinfecting the filter standpipe using chlorine solution, flushing filters with ~100L of water following installation and cleaning, and preparing and translating standardized Biosand filter training materials based on 8 key educational points.

Well field-testing in the 17 IBS villages consisted of 109 samples analyzed for H_2S producing bacteria and enumeration of 67 fecal coliform and 23 *E.coli* samples using the membrane filtration technique. Public wells, in general, were found to offer much safer drinking water than private wells with 20% of public wells and 39% of private wells testing positive for fecal coliform bacteria. More importantly, the concentration range of private tubewell fecal coliform bacteria was found to be much greater (1cfu/100ml to 500 cfu/100ml) than that of public wells (1cfu/100ml to 14cfu/100ml).

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I dedicate this thesis to my stepfather, John Faltis, without whose encouragement I would never have come to MIT.

I would like to thank all those in my life, both presently and in the past, who have contributed or are contributing to the growth and happiness of my person. I could only hope to do as much for you as you have done for me.

This includes those who have helped me over the past 9 months as I have been learning about this amazing filter and its application in Lumbini, Nepal. I would first like to thank Bhikkhu Maitri, Asmita Chettri, Maya Panday and everyone else at the International Buddhist Society for being such gracious hosts in Lumbini, Nepal. I would also like to thank Dr. David Manz and Camille Dow Baker for inventing, teaching, and sharing the Biosand filter with thousands all over the globe (myself included).

Special thanks to Hannah Sullivan whose advice and friendship in the field was invaluable; to Susan Murcott, my advisor, whose drive to help others is always inspiring; and to the rest of the Nepal group. I smile widely when I think of you all.

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Figures and Tables

1 Introduction

Safe, potable drinking water is a pressing concern for all of humanity. Whether it is the microbial contamination of drinking water in the southern Terai of Nepal, the sewage that flows directly into the Charles River every time it rains, dry wells on the Hopi reservoir, acid mine drainage in West Virginia, or mercury in Maine, water supply and quality are essential to human survival. While water-related illness is most dire in developing countries, developed countries like the United States are not without drinking water quality problems. Outbreaks of hepatitis A, viral gastroenteritis, cholera, typhoid fever, and giardiasis in the U.S. have all been traced to groundwater contamination (Bitton and Gerba, 1984). Additionally, the Surface Water Treatment Rule of the National Primary Drinking Water Regulations (1989) recognizes the need for treatment of all surface waters in the U. S. including protected watersheds due to the presence of protozoa such as *Giardia* and *Cryptosporidium.* (Glicker, 1991) Highly resistant to chlorine, Cryptosporidium is currently of particular concern after it caused 400,000 cases of severe diarrheal illness in Milwaukee during the spring of 1993. The difference between water shortages and contaminated lakes, rivers, and aquifers in the developed world and that of the developing world boils down to options. Wealthy are those who can heat water to bath in, who flush water safe for drinking down toilets, who water lush green lawns in deserts, and who know not where their water comes from.

According to the United Nations (UNICEF, 1999), 1.7 billion people or 28% of the world's population are without access to clean drinking water, and 3.4 billion are without adequate sanitation. Waterborne diseases are the leading cause of childhood death worldwide (UNICEF, 1999). As our world population continues to grow most rapidly in developing regions, existing drinking water sources will undoubtedly both worsen in quality and lessen in quantity (Gupta, 1992). These statistics, while striking, do not sufficiently capture the importance of the current drinking water crisis. While the United Nations declared the 1980s to be the International Decade of Water and Sanitation, top-down international aid projects have failed to reach the majority of those in need, those who are dying without any way to help themselves or their children. Our inadequacy to properly address this issue is well documented. Many have come up with solutions.

Economist Bjorn Lomborg, author of The Skeptical Environmentalist (2001), even went so far as to suggest that the costs of complying with the Kyoto protocol for one year could provide clean water and sanitation services for the whole developing world, saving 2 million lives, and keeping half a billion people from serious illness. The point is neither to confirm his statistics nor to take money away from other relevant environmental problems, but rather that drinking water is a current problem that demands immediate thought and resources. In the absence of millions of dollars necessary to build large treatment systems in cities and small community systems in rural areas, several researchers have developed point-of-use water treatment technologies that can provide clean water to those in need today. One of such technologies, an intermittently operated slow sand filter called the Biosand filter is the subject of this study. Its design, function, and implementation in rural Nepal will be explained in detail over the following pages.

1.1 Point-of-use versus community-scale treatment

Water treatment options for the developed world are broad. With capital, materials, technical expertise, and energy readily available, drinking water issues can be solved by properly allocating resources and through municipal and industrial regulation. Because of the capital-intensive construction of centralized treatment plants and the difficulties of operation and maintenance in remote areas, centralized treatment is not practical in the foreseeable future for many regions in the developing world. Alternatively, decentralized point-of use or household-scale water purification systems may provide an economic alternative to drinking water directly from sources including often-contaminated piped water in areas serviced by a water distribution system (Gupta, 1992). Allowing the user to treat water immediately before drinking, recontamination of stored water becomes less likely. While there is not much literature directly available on point-of-use drinking water treatment systems appropriate for developing countries, working to conceive and implement such systems based on basic engineering concepts, water treatment processes, and scaling down large water treatment systems can be a positive step towards providing safe water to those in need. To be appropriate for the developing world, such technologies must be simple, economically sustainable, socially desirable, and able to be built and maintained locally with available materials. Their function must be understood and accepted by community members who may not be accustomed to treating water. Slow sand filtration, chlorination, solar disinfection, ceramic filtration, and boiling are all examples of point-of-use drinking water treatment technologies currently available and in use in developing countries.

1.2 Continuous slow sand filtration

With no chemicals or highly technical design variables, slow sand filtration is an ideal technology for developing country drinking water treatment applications. Consisting of water flowing downward through sand media, slow sand filtration has been used in diverse locations of the world such as London and Peru for the past two centuries. (Collins, 1991) Slow sand filtration has been proven to successfully remove microbial contamination, although just recently have the more precise methods of removal been explored. For example, researchers have moved beyond just demonstrating that biological processes are integral to slow sand filtration pathogen removal and into identifying how these removal mechanisms actually work. An observed dearth in slow sand filtration literature between 1915 and 1970 (Weber-Shirk, 1997a) can be attributed to the developed world's focus on highly technical, automated designs that can be readily patented with profits secured and operation more easily replicated. With conventional drinking water treatment depending on disinfectants such as chlorine, new concern about the potential health risks of disinfection byproducts and pathogens resistant to these disinfectants has mounted. (Rittman, 1996) This concern has resulted in the recent revival of interest, study, and application of slow sand filtration in developed countries. Since 1995, at least three New England towns (Gorham, NH, Rutland, VT, and Milo, ME) have built new, innovative slow sand filtration systems (Josin 1997). This more aesthetically pleasing treatment depends on natural physical, chemical, and biological processes for

contaminant removal. With filtration rates 50-100 times slower than those of rapid sand filters, a much larger sand bed area is required for a given capacity. In addition, cleaning is accomplished by scraping or filter harrowing as opposed to the more frequent backwashing required by rapid sand filtration (Ashe 1999). With minimal material and no chemical or electrical requirements, traditional slow sand filtration technologies, used on a community scale for several centuries, have been tailored for developing country applications.

1.3 Biosand filter introduction

Recognizing its ideal developing country applications, Dr. David Manz, formerly of the University of Calgary and now of Davnor Water Treatment Technologies, Ltd., further modified community slow sand filtration technology for intermittent operation on a household level. This innovative intermittent design, called the Biosand filter, contains five-centimeters of standing water above the fine sand media which functions to preserve biological activity when the filter is not being used. Because of its relatively small surface area, this scaled-down filter also has a much higher flow rate of 0.6 m/h (or 30L/hr) compared to 0.1 m/h of traditional slow sand filters. Much like its continuous counterpart, the Biosand filter requires no chemical additives with its primary materials consisting of sand and concrete (which can be found anywhere). Filter cleaning is simple and only necessary when the flow rate drops below a desirable level. Simply breaking up the biofilm present in the top ~5cm of sand by stirring gently and replacing the highly turbid water with relatively clean water will resume adequate flow of the Biosand filter, and thus there are no costs associated with filter cleaning or maintenance. This cleaning process is a smaller version of the filter harrowing of continuous slow sand filter treatment plants described by Collins et al (1991). This cleaning allows for the maintenance of a high bacterial population and minimally affects performance. The design and operation of the Biosand filter will be discussed in detail in Chapter 4 while the pathogen removal mechanisms of continuous slow sand filtration will be discussed in Chapter 3. Chapter 2 will serve to place this innovative slow sand design in context with its point-of-use technology peers, while Chapters 5 and 6 will explain field testing methodology and implementation of a Biosand filter pilot project in rural Nepali villages.

1.4 Thesis objectives

- To evaluate the technical performance, social acceptability, and economical sustainability of the Biosand filter in relation to other household drinking water treatment options

- To better understand the biological processes of intermittently operated slow sand filtration

- To outline essential components of Biosand filter implementation in developing countries

- To describe field methodology performed in January 2002 and to recommend analysis modifications for future field work in Lumbini, Nepal

- To report results, observations, and conclusions regarding the Lumbini Biosand Pilot Project and well survey

- To assist (in some small way) in the provision of clean drinking water to all the Earth's inhabitants

2 Comparison of point-of-use water treatment technologies

A variety of point-of-use water treatment technologies have been developed and implemented by international aid agencies, non-profit organizations, educational institutions, and individuals. Over the past 3 years, students in MIT's Environmental Masters of Engineering program have traveled to developing countries to assess the demand for point-of-use water treatment technologies, the appropriateness of these systems, the success of existing community projects, and the implementation of new pilot projects. This chapter aims to briefly evaluate several of the technologies currently under investigation in relation to the Biosand filter. This is meant to place the Biosand filter in context among its peers, highlight design advantages, and expose areas for potential improvement.

2.1 Evaluation criteria

If real reductions in waterborne disease are the desired result, many factors must be considered before implementation of point-of-use water treatment technologies. Pathogens contaminating water supplies must be identified, user demand accessed, and an appropriate, cost-effective technology selected. The following criteria aim to incorporate both the hard technical and the softer social issues relevant when considering point-of-use water treatment. After acknowledging that certain issues can only be determined on a case-by-case basis, categories of technical performance, social acceptability, and economical sustainability are subdivided into relevant criteria that will be used to evaluate different technologies. Material presented in this section is a synthesis of the author's personal experience with that of Murcott (1999), Kalbermatten (1980), and the Centre for Affordable Water and Sanitation Technology (CAWST, 2001).

2.1.1 Case-by-case issues

Diverse problems dictate cleverly sculpted solutions. For example, if surface water is the primary drinking water source, people are getting sick from bacterial dysentery, and concrete is a common material for house building, the Biosand filter may be a good solution. If, however, water piped directly to homes is high in fecal coliform bacteria, low in turbidity, and cholera is of concern, maybe household chlorination may be more appropriate. Thus, additional variables to consider include the condition of water source, the routes of pathogen transmission through water, the methods of water extraction and collection, the number of households using a source, and the general health level of those households (Earp 1992). The ultimate goal of drinking water treatment is to maximize the health and quality of life benefits to those drinking the water. The primary criteria for evaluating such technologies should be that they remove those pathogens that make local populations sick.

2.1.2 Pathogens

Published in 1876, Robert Koch's germ theory of disease proved that specific microorganisms cause specific diseases, a theory that many now take for granted. Research stemming from this knowledge has resulted in the identification of significant waterborne pathogenic microorganisms, characteristics of their transport, and their infection potential. (Table 2.1) Once the connection between a microorganism and the disease resulting from infection has been made, it is important to identify both the magnitude of risk associated with infection of this pathogen and how it is best removed from water sources. The majority of waterborne pathogens can be categorized as bacteria, viruses, or protozoa.

Bacteria are generally between 0.3-2um in size although "ultramicrobacteria" or starved bacteria can be less than 0.3um (Costerton, 1993). Bacteria *salmonella typhi* and *vibrio cholerae* cause typhoid fever and cholera respectively. Vibrio cholerae are gram-negative, curved rod bacteria that reside in the small intestine. Similar to other bacteria, *vibrio cholerae* can be destroyed easily by disinfectants. A large dose of cholera vibrios ($10^8 - 10^9$) is necessary for infection (Madigan, 2000). Common sources of bacteria are human feces or fecally contaminated food. In 1991 alone, 284, 979 cases and 3,070 deaths attributable to cholera were reported in Peru (Craun, 1991). These outbreaks have spread to Ecuador, Columbia, Chile, Brazil, Mexico, and even the United States.

Viruses, microorganisms which need a host to multiply, are very different than bacteria. They are much smaller in size (0.02-0.3 um), have a very low infectious dose (possibly only one organism), and can result in diseases such as the polio virus (0.028 um diameter), Norwalk virus, and hepatitis A virus. Like bacteria, they are associated with fecal matter, can be destroyed by disinfectants, and present significant health risks to an infected person (Madigan, 2000).

Entamoeba hystolytica, *Giardia intestinalis*, and *Cryptosporidium parvum* are all protozoan microorganisms that result in Amebiasis, Giardiasis (an acute form of gastroenteritis), and Cryptosporidiosis, respectively. *Giardia intestinalis* is a flagellated protozoan when in its trophozoite phase while its resting stage is in cyst form. Giardia is present in 97% of surface waters in the US with animals such as beavers and muskrats as carriers. Similarly, *Cryptosporidium parvum* is an intestinal pathogen in dairy cattle (Fogel, 1993). These protozoa are relatively large with *Giardia intestinalis* cysts being 7-12um and *Cryptosporidium parvum* cysts being slightly smaller or 3-10um. Additionally, while easily filtered through media both Giardia and Cryptosporidium cysts are very resistant to disinfectants. Any unfiltered water supply is, therefore, susceptible (Glicker, 1991).

Table 2.1: Orally transmitted waterborne pathogens and their significance in water supplies

Pathogen	Heath Significance	Persistence in Water Supplies[a]	Resistance to Chlorine[b]	Relative Infective Dose[c]	Important Animal Reservoir
Bacteria					
Campylobacter jejuni, C. coli	High	Moderate	Low	Moderate	Yes
Pathogenic Escherichia coli	High	Moderate	Low	High	Yes
Salmonella typhi	High	Moderate	Low	High[d]	No
Other salmonellae	High	Long	Low	High	Yes
Shigella spp.	High	Short	Low	Moderate	No
Vibrio cholerae	High	Short	Low	High	No
Yersinia enterocolitica	High	Long	Low	High (?)	No
Pseudomonas aeruginosa[e]	Moderate	May multiply	Moderate	High (?)	No
Aeromonas sppl	Moderate	May multiply	Low	High (?)	No
Viruses					
Adenoviruses	High	?	Moderate	Low	No
Enteroviruses	High	Long	Moderate	Low	No
Hepatisis A	High	?	Moderate	Low	No
Enterically transmitted non-A, non-B, hepatitis viruses, hepatitis E	High	?	?	Low	No
Norwalk vivurs	High	?	?	Low	No
Rotavirus	High	?	?	Moderate	No(?)
Small round viruses	Moderate	?	?	Low(?)	No
Protozoa					
Entamoeba hystolytica	High	Moderate	High	Low	No
Giardia intestinalis	High	Moderate	High	Low	Yes
Cryptosporidium parvum	High	Long	High	Low	Yes
Helminths					
Dracimculus medinensis	High	Moderate	Moderate	Low	Yes

Source: World Health Organization (1993)

? – not known or uncertain

[a] Detection period for infective stage in water at 20 degrees C: short, up to 1 week; moderate, 1 week to 1 month long; long, over 1 month.

[b] When the infective stage is freely suspended in water treated at conventional doses and contact times. Resistance moderate, agent may not be completely destroyed.

[c] Dose required to cause infection in 50% of health adult volunteers. May be as little as one infective unit for some viruses.

[d] From experiments with human volunteers

[e] Main route of infections is by skin contact, but can infect immuno-suppressed or cancer patients orally

Indicator organisms such as the coliform group have traditionally been used to represent the presence of pathogens that, in practice, are difficult to isolate and quantify on a regular basis. Coliform bacteria are aerobic and faculty anaerobic, rod-shaped bacteria that ferment lactose with gas formation within 48 hr at 35°C (Madigan, 2000). Fecal coliforms are a thermotolerant subset of the total coliform group distinguished only by the high temperature, 44.5 ± 0.2°C, at which they ferment lactose in 24 ± 2 h. Because fecal coliform bacteria generally inhabit the intestinal tract of warm-blooded animals and are present in great quantity in receiving waters, they have traditionally been regarded as a good indicator for pathogens of fecal origin.

While current standards for indicators are changing, fecal coliform, *E. coli*, and H_2S producing bacteria were selected for use in this study to indicate the presence of pathogens, due to their prevalence in the existing literature and the field techniques available for their analysis in rural Nepal (See Chapter 5 for description of field methods used). It is important to note, however, that in complex natural environmental systems and during treatment, the existence and behavior of indicator organisms may differ greatly from the microorganisms they supposedly represent. For example, since most microbial indicator organisms are themselves bacteria, their absence following chlorination would be expected while *Cryptosporidium parvum*, a protozoan, could be present. Because only indicators, the results of indicator tests do not deem water "clean," but these are simply an available way to identify probable contamination when full laboratory facilities and funds are not available.

2.1.3 Technical performance

The technical performance of point-of-use water treatment technologies can be measured in several ways. First and foremost (as mentioned above), the technology must remove the viral, bacterial, and protozoan pathogens that result in sickness or all other evaluation criteria lose relevancy. In addition to those pathogens that cause disease following ingestion, there are also those that result in water-washed diseases such as trachoma, which causes blindness (UNICEF et al, 2000). For this reason, technologies must treat sufficient quantity of water to allow for dishwashing, cleaning, and personal hygiene uses in addition to drinking. The third and equally important technical criterion is design robustness. This includes how often maintenance is required, how prone the design is to malfunction, and the ability for local repair if breakage does occur. For example, a Peace Corps volunteer returned to an African village shortly after a new project was implemented to find solar panels being used as soccer goals. Such foreign design with parts only available thousands of miles away, provides no avenue for local maintenance and will always require outside involvement. People in developing countries are often extremely resourceful, but they must be given the opportunity. The robustness of a design also depends on how obvious technology failure is to users. Because daily monitoring of point-of-use devices is impossible, there should be a clear indication that water is unsafe for drinking.

2.1.4 *Social acceptability*

As an attempt to synthesize complex "soft" criteria into something tangible, social acceptability or the "appropriateness" of point-of-use water treatment options can be divided into the following categories:

- Demand for technology as demonstrated by user willingness-to-pay or contribute labor
- Opportunity for community participation that will provide a sense of ownership to users
- Simple technology with obvious importance to water providers (primarily women)
- Not time consuming to maintain
- Culturally acceptable
- Minimal impact on current social structures

2.1.5 Economical sustainability

The final evaluation category is that which is most valued by free market capitalists. Given the current state of our global economy, for any new project to succeed it must prove itself economically sustainable. This category should consider the following:

- Total initial investment cost in addition to monthly recurrent costs to users
- Opportunity to establish a micro-enterprise to construct, distribute, and maintain the technology
- User willingness-to-pay initially and for continuing operation and maintenance (if required)

When implementing such technoloies in developing countries the cost factor should be broken down into the cost of each part (if the units are not pre-made) including shipping (if not made locally) and the manufacturing cost. Areas of unnecessary spending can be located with this deeper analysis. The $50 price of the Gift of Water filter represents not only filter materials, manufacturing, and shipping, but also the cost of paid technicians and an education and maintenance program. The cost of producing chlorine within a country should be considered versus the cost of importing it from elsewhere. Also relevant is the cost of transport of a filter that needs to be replaced every year or chlorine that needs to be supplied every month versus the one time only installation cost of a filter such as the Biosand.

2.2 Alternatives

With all the above criteria in mind, brief descriptions of point-of-use technologies will be provided along with relevant advantages and disadvantages of each technology. The intent of this section is to explore the field of household water treatment in general, so that strong points of each technology can be replicated wherever possible and shortcomings minimized.

2.2.1 *Biosand filter*

An intermittently operated slow sand filter, the Biosand filter, is an appropriate point-of-use water treatment technology for developing countries. Outlined below are its relevant characteristics, which will be further detailed throughout this thesis.

Technical performance:

- 100% removal of protozoa, 99.9% removal of viruses (Canadian Water Treatment Research Institute, 1996)
- 99.5% of bacterial removal in laboratory settings (Lee, 2001)
- Bacterial removal varies from 60-99.9% based upon presence of biological layer (Davnor, 2002)
- Time necessary for formation of biolayer during start-up and following cleaning[1]
- Simple, robust design (readily available materials, internal piping, heavy and durable)
- Need for cleaning dictated by slow flow rate (natural control, no need for monitoring once operating effectively)
- Substantial water provision (30 L/hr flow rate)

Social acceptability:

- Opportunity for community participation in filter construction
- Easily maintained, cleaned by users
- Filtered water is cool and clear
- No chemicals added, no consumable parts
- Concrete is a common house or roofing material

Economical sustainability:

- Costs vary by region: US$27 in Nepal (Lee, 2001), $15 in Bangldesh, and $8 in Vietnam (CAWST, 2001)
- Opportunity for labor contribution during media preparation and concrete mixing (to lower initial capital costs)
- No costs associated with operation and maintenance
- 8+ year lifetime[2]
- Good micro-enterprise for local artisans

2.2.2 *CDC Safe Water System*

The CDC's safe water system approach consists of disinfection with locally available chlorine (sodium hypochlorite solution generated from brine or purchased as bleach), safe water storage, and hygiene promotion (CDC, 2002). The addition of chlorine serves two purposes. One is the primary disinfection or initial kill of *Giardia* cysts, bacteria, and viruses. The other, secondary disinfection, is the maintenance of a disinfectant residual, which prevents regrowth of microorganisms during transport and storage. This system is not unlike the use of chlorine as a disinfectant during water treatment in developed

[1] This time is a function of raw water source quality and quantity as well as time and is, thus, location specific. CAWST (2001) has reported full biological recovery 2 days following cleaning.
[2] Biosand filters installed in Valle Menier, Nicaragua in 1993 are still in use today (2002).

countries except it is scaled down from a centralized treatment plant level to an individual household level. See the CDC Safe Water Systems manual (CDC, 2002) or Sullivan (2002) for a complete discussion of the CDC Safe Water System.

Technical performance:

- Bacteria and viruses killed in 30 minutes of contact time with 0.2-0.5mg/L free chlorine residual (CDC, 2002)
- To kill *Giardia*, 1.5mg/L residual chlorine and ten minutes are necessary (CDC, 2002)
- *Cryptosporidium* oocysts are extremely resistant to chlorine
- Chlorine demand varies with water quality, water quality varies seasonally and with precipitation
- Water should be free of organic matter
- Chlorine provides residual protection against possible recontamination

Social acceptability:

- Chemical taste is a problem for some
- Airtight storage protected from direct sunlight and heat is important to prevent degradation of chlorine residual

Economical sustainability[3]*:*

- Local supply of hypochlorite must be continuously available
- Strength of hypochlorite solution must be relatively constant
- Minimal initial cost for 2 plastic 20 liter water containers (~$2.50 per 20L container in Nepal)
- ~US$1 per month cost for treating 24 liters per day[4]

2.2.3 *Solar disinfection*

The solar disinfection (SODIS) treatment process consists of filling plastic bottles with water and exposing them to sunlight. SODIS operates on the principle that sunlight-induced DNA alteration, photo-oxidative destruction, and thermal effects will inactivate microorganisms. To achieve adequate disinfection, an area should receive at least 500W/m^2 of radiation for 5 hours. Several MIT Masters of Engineering theses have focused on SODIS in Nepal and Haiti (Khayyat, 2000; Oates, 2001; Smith, 2001; Parsons, 2002).

Technical performance

- Suitable for water with turbidity of less than 30 NTU

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[3] See Morganti (2002) for complete discussion of the economically sustainability of sodium hypochlorite generation as a micro enterprise for household scale chlorination.

[4] This cost came from Morganti's (2002) work in Nepal. It assumes a cost of 17 NPs (US$0.23) per bottle of hypochlorite solution. 24 liters corresponds to the minimum amount of water that should be treated per day for a household consisting of 6 people.

- Disinfects bacteria and viruses, its effect on cysts and worms has not been fully researched
- Subject to seasonal variations and cloudy days

Social acceptability:

- Only small amounts typically 1-2 liter volumes can be disinfected at a one time
- Water is heated, yet cool water is often preferred
- No physical change in water's appearance other than temperature increase
- Uses plastic bottles which are easy to handle, convenient for storage and transportation, and reduce risk of recontamination

Economical sustainability:

- Does not require consumables except for plastic bottles

2.2.4 Ceramic filter by Potters for Peace (1999)

Invented by Fernando Mazariegos of the Central American Research Institute for Industry, this ceramic filtering system consists of 4 individual parts: a porous clay filter treated with colloidal silver, a larger recipient vessel, a spigot, and a lid. The porous clay filter sits inside the recipient vessel, and water filters through the clay. The filtering unit is composed of clay and sawdust. The sawdust burns out during the firing to create pores through which water flows. Colloidal silver, an alternative disinfectant, is painted on the filter after firing. The role of the positively charged silver is to inactivate bacteria by disabling an oxygen-metabolizing enzyme. This filter is included in the UN *Appropriate Technology Resource Material Manual.* A study done by AFA Guatemala concluded that the filter resulted in a 50% reduction in diarrhea among users. A MIT Masters of Engineering thesis by Rebecca Hwang (2003) will focus on the effectiveness of the filter with and without colloidal silver.

Technical performance

- Eliminates bacteria (National Institute for Water Resources, National Autonomous University of Nicaragua)
- Effectiveness dependent on pore size and the correct concentration of colloidal silver for every new clay body (Mazariegos, 1999)
- The filter blocks quickly if source water is turbid, and needs regular scrubbing and maintenance to ensure maximum flow rate
- Possible health effects of colloidal silver
- Slow maximum filtration rate (1-2L/hr)

Social acceptability

- Need to scrub based upon turbidity, concentration of source water, and frequency of use (~once per month) (Lantagne, 2002)
- Ceramics are a traditional trade in many locales

Economical sustainability

- Need to replace inner ceramic filter every year for $8

- Initial capital cost of one filter ($8) plus cost of recipient vessel

2.2.5 String wound & granular activated carbon filter by Gift of Water, Inc.

The Florida-based non-governmental organization Gift of Water, Incorporated (GWI) (Warwick 1999) developed, produces, and distributes a two-tier plastic bucket filtration system in rural Haiti. The top bucket contains a 1-micron nominal sediment filter with synthetic cotton string tightly wound around a porous core. Complete with handle, the top bucket can be detached and used to collect water from a water source. The bottom bucket, which stores the purified water, contains an activated carbon filter to remove chemicals and improve taste. In addition, sodium hypochlorite in the form of bleach (5.25% chlorine) is added to first inactivate microorganisms in the top bucket and then to provide residual in the filtered water in the bottom bucket so that regrowth does not occur (Warwick 1999).

Gift of Water has implemented their low cost purifier technology in the homes of 22,000 people in Haiti. Their program success is based on their detailed education and maintenance program and consistent outside funding. The maintenance program consists of a network of local community technicians assigned to each monitor 50-100 homes that use the *Gift of Water* filter. Haitian workers assemble the systems in Haiti. Bleach is currently imported from the US and Dominican Republic.

Technical performance

- Removes turbidity, bacteria, and particulate matter
- No studies have been conducted on removal of viruses or protozoa (although the cotton filter may remove protozoa and chlorine should inactivate viruses)[5] (Lantagne, 2002)
- Flow rate of 19 liters/hour
- Possible health implications of disinfection by-products, such as trihalomethanes
- Provides residual protection against possible recontamination

Social acceptability

- High continued usage rate (GWI aims for 70 percent correct usage rate based on chlorine residual)
- Light, easy to transport
- No way to know when carbon filter is saturated, GWI policy is to change every 6 months

Economical sustainability

- Filters cost US$15 for parts and shipping and US$50 total for the first year of maintenance, training and installation
- Haitian families only pay approximately US$1.88 (depending on community)
- Dependent on subsidies provided by churches and other donors
- All parts except the plastic buckets are imported

[5] Borucke (2002) did, however, find that Giardia surrogates (latex micro-spheres of 6um diameter) were not removed by the cotton filter.

- Requires constant supply and distribution of chlorine
- Activated carbon filter must be replaced every 6 months

2.3 Summary

The purpose of this comparison section is to identify both the strengths and the weaknesses of some of the major point-of-use drinking water treatment technologies potentially appropriate for developing country application. Integrating the above knowledge, it is important that all interventions are based upon demand, that potential users are given the option to choose an appropriate technology, and that there is community inclusion in decisions about these appropriate water treatment options. The role of researchers is to investigate and provide a selection of options based on this user feedback while also working in an overall collaborative partnership with users. With past aid programs as the example, projects that require minimal operation and maintenance are generally the most successful. With ozone and UV radiations acting as primary disinfectants in many new treatment plants, chemical disinfectants are in the process of being phased out of water treatment in developed countries. The advantage of the Biosand filter over solar disinfection and chlorination is in its ability to remove protozoan pathogens (even without biological growth). In relation to other filtration systems, the Biosand has the advantage of its high flow rate (30L/hr), which can treat sufficient water for both drinking and hygienic purposes and its one time only initial cost. Also with minimal maintenance and no additional materials required, the Biosand filter has clear advantages over technologies that require non-native materials (GWI filter, sometimes chlorine) or the re-supply of materials (chlorine, filter parts, ceramic filter, activated carbon part of the GWI filter) especially when villages are only seasonally accessible and incomes undependable. In addition to the cost of such materials, their transport requires time and effort. Important for social acceptability, a technology that demands little from its user is most desirable. Clear challenges of the Biosand filter are its dependence on biological mechanisms for the removal of bacteria, and the difficulty of conveying this importance to users. Unlike the other above-mentioned household drinking water treatment options, the Biosand filter's shortcomings can be addressed by an education system associated with filter installation and is not a fault of the technology design, which itself is quite robust. The basic principles of this design will be clarified in the following two chapters, and the complexity of this seemingly simple technology exposed.

3 Continuous slow sand filtration

Drinking water has been treated by continuous slow sand filtration systems for the past two centuries. Designed to optimize pathogen removal efficiency, slow sand filtration depends on biological, physical, and chemical processes. Just recently, current research has begun to investigate just why and how slow sand filtration works. In addition, great progress applicable to slow sand filtration has been made in the fields of environmental microbiology and groundwater transport. This chapter will first present processes that affect microbiological transport through media in Section 3.1. The purpose of this section is to identify and summarize current knowledge about processes that could potentially affect microorganism removal in slow sand filters. Since so few papers have been published specifically about removal mechanisms in slow sand filters, this section aspires to identify as many relevant removal processes as possible. Section 3.2 will describe the process of slow sand filtration and summarize current knowledge in the field. The final section of this chapter will identify design and process variables that have been optimized to maintain removal efficiencies. The intent of this chapter is to provide background essential for the discussion of intermittently operated slow sand filters in Chapter 4.

3.1 Microbiological transport through media

Many of the factors that affect transport in groundwater have been examined in bench-scale flow-through column tests. While it can be difficult to scale these up to heterogeneous, not-completely-saturated real aquifer conditions, these bench-scale experiments are ideal for studying of the factors that affect transport of microorganisms through saturated media. Both hydro-geological (abiotic) and microbial (biotic) in nature, these processes include reversible and irreversible attachment to solid surfaces, straining, predation, motility, changes in the physiological state of the cell (including lysis), sedimentation, and other less-understood mechanisms. Even some mechanisms not obviously applicable to slow sand filtration are included in this discussion as there is still much to be learned about mechanisms that will potentially affect removal (especially those of biological nature).

3.1.1 Reversible and irreversible attachment to solid surfaces

While flowing through media, a tracer can be used to observe attachment to solid surfaces. The breakthrough curve of a conservative tracer will be notably different from that of microorganisms when microorganisms interact with the media surface. Assuming irreversible and reversible attachment sites for microorganisms, Harvey et al (1991a) identified a collision efficiency factor that represents the physiochemical factors that determine irreversible microbial attachment. These factors include: median grain size, travel distance, porosity, and single collector efficiency (rate at which microorganisms contact a single sand grain divided by the rate at which they move toward the grain). The single collector efficiency parameter is comprised of the following: colloid and grain radii, fluid viscosity, fluid approach velocity, porosity, density of groundwater and microorganism, acceleration due to gravity, temperature, Hamaker constant, and Bolzmann's constant (Harvey, 1991b).

These attachment or adhesion processes must also take into account a variety of chemical interactions between microbial cells and porous media including hydrophobicity and charge. The composition of the lipopolysaccharide layer and the presence of specific proteins in cell surfaces, appendages, and extracellular polymers can also play a role in determining transport potential. For reversible or irreversible adhesion to occur there must first be an initial interaction between the cell surface and particle surface by diffusion, convective transport, or active movement of the cell surface. Reversible interactions are a balance of repulsive electrostatic interactions, attractive van der Waals forces, and hydrophobic interactions. Because both microorganisms and media are generally negatively charged, repulsive electrostatic interactions result. Lipotichoic acids on the surface of gram-positive bacteria, lipopolysaccharides on the surface of gram-negative bacteria, and viral protein coats can all result in negative microbe charge. Carboxyl functional groups (that dissociate with increases in pH) associated with organic matter and isomorphic substitutions (replacement of particular ions in media structure with other more charged ions) both result in negatively charged media, which repel negatively charged microbes. However, if cations are present in solution[6], they will be attracted to the vicinity of the negatively charged media surface. Together, these interacting cations and anions will have a neutralizing effect, and opportunity for attachment will, then, exist (Huisman and Wood, 1974).

Van Loosdrecht et al (1990) compared the adhesion of a variety of bacteria to hydrophobic (polystyrene) and hydrophilic (glass) surfaces. He concluded that hydrophobic attraction dominated adhesion to polystyrene while bacterial cell surfaces are highly hydrophobic regardless of their charge. However, cells with a high surface charge and cells with hydrophobic surfaces showed little adhesion to glass (hydrophilic) surfaces. Thus, adhesion typically decreases with decreasing hydrophobicity of either the solid surface or the cell surface and adhesion generally increases with decreasing cell surface charge.

Because of their varying characteristics, these adhesion processes can influence microorganisms quite differently. That which holds true for bacteria may not hold true for viruses. An example of this is that while bacterial diffusion is generally negligible, viral (<1um diameter) diffusion can be significant in soils. In addition, hydrophobic effects and electrostatic repulsion dominate virus sorption. Solutions of low-ionic strength, for example, do not readily sorb or release viruses from soil particle surfaces (Goyal and Gerba, 1979). Bales et al (1993) demonstrated that soil pH is the single most important factor influencing viral adsorption to soil, and that soils with pH less than 5 favor virus adsorption.

3.1.2 Straining

Physical filtration effects or straining are important physical removal mechanisms for particles greater than 5% of the diameter of the soil particle. For example, sand with a diameter of 0.1mm will strain out particles that are 5um or larger. (Herzig et al, 1970)

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[6] Ionic strength of medium is the concentration of anions and cations in solution.

Viruses are much less than 1um and must, therefore, be removed by other means (Gerba et al, 1991).

3.1.3 Changes in the physiological state of the cell

Change in shape and propensity for attachment can greatly impact transport potential. (Harvey, 1991a) When nutrients are plentiful, most cells produce exopolymers that coat the outer surface of the cell and can increase the effective diameter and length of the cell. It has also been demonstrated that when cells are in a starved state (when nutrients are limiting), they typically shed their glycocalyx or outer layer (decrease in size to 0.3 um or smaller) and stop producing exopolymers. When nutrients become available again, these "ultramicrobacteria" such as a p-nitrophenol degrader can be resuscitated to pre-starving sizes and shapes (Costerton, 1993). Weiss et al (1995) found that small, round bacteria were the most likely to be transported through columns packed with quartz sand. Thus, it can be concluded that the absence of nutrients could result in the rapid transport of a microbe that would otherwise be trapped. Spore formation for some gram-positive species can have a similar effect of increased transport potential. Furthermore, the survival and metabolic potential of introduced microbes such as those present in influent water will be challenged by the different temperature, pH, soil texture, and presence of indigenous organisms. Lysis can occur under extremely unfavorable conditions (Harvey, 1991a).

3.1.4 Predation

Predation by protozoa threatens pathogenic microorganisms as they move into a new environment. Traditional ecosystem predator-prey interactions exist between protozoa and bacteria resulting in more particle-sorbed bacteria when protozoa are present (Postma et al, 1990). Harvey (1991a) also mentions parasitism by bacteriophage and predatory bacteria (*Bdellovibrio* species) as a threat to incoming bacteria.

3.1.5 Motility

Motility or intrinsic mobility of cells cellular appendages involved in motility (flagella) can increase microbial transport while those involved in attachment (pili and fimbriae) can reduce transport potential (Harvey, 1991a, Madigan, 2000).

3.1.6 Sedimentation

Sedimentation or the settling action within pores, is a process by which particulate suspended matter and associated microbes are gravitationally depocited onto solid surfaces. Because settling velocity is a function of particle density, particle diameter, water density, and water viscosity, the larger and denser the particle, the quicker it will settle (Huisman and Wood, 1974). Bacteria are assumed to demonstrate neutral or near neutral buoyancy, and therefore are not affected by sedimentation unless associated with larger settling particles.

3.1.7 Other less understood mechanisms

In addition to those already discussed, other mechanisms have been studied in numerous laboratory experiments including the effects of small pore exclusion, attachment reversibility, chemotaxis, microbial abundance upon sorption kinetics, flow velocity,

ionic strength, the influence of specific chemicals, sorption, rates of attachment and detachment, microbial surface residence times, cell hydrophobicity and surface charge, mineralogy, and clogging. Because these studies are numerous and not specific to slow sand filtration, they will just be recognized here.

Many of these mechanisms were more elegantly summarized in the following definition of biofilm communities:

> "Formation of the detailed structure of a bacterial colony is a combination of two separate factors intrinsic and extrinsic. Intrinsic factors are products of the genetics of the cell itself. They determine the morphology of the individual cell, the mode of cell reproduction, the possession of extracellular appendages (flagella, fimbriae, pili, etc.) production of extracellular products (exopolysaccharides, proteins, etc.) motility, energy metabolism, pigment formation and so on. Extrinsic factors include the prevailing physico-chemical environment which influences the physiology of the cell plus the transport of solutes into and out of the growing colony and the inevitable formation of solute diffusion gradients within the colony and the surrounding medium." (Wimpenny, 2000)

3.2 Removal process of slow sand filters

There is a wealth of literature demonstrating the effectiveness of slow sand filters in reducing total coliforms 1-3 log units, enteric viruses 2-4 log units, *Giardia* cysts 2-4 log units, and turbidity to less than 1.0 NTU. After an initial 1-3 week period of filter ripening, biological, physical, and chemical processes act almost symbiotically to remove these microorganisms and turbidity. This section will briefly describe these removal mechanisms and filter ripening.

3.2.1 Filter ripening[7]

Following slow sand filter installation, gravity-fed influent water flows through a bed of clean homogenous fine sand (~0.1-0.2mm diameter) maintaining saturated conditions above and within the sand bed. Initially, slow sand filter performance is based solely on the physical-chemical removal mechanisms of the sand media and flowing water. Over time, particulate and organic matter settles on the solid surface resulting in system head loss and increased removal of turbidity and microorganisms. This resulting inert layer of settled particles above sand media is known as the *Schmutzdecke* or filter cake. Dissolved organic carbon, dissolved oxygen, and nutrients present in the influent water support elevated biological populations within the *Schmutzdecke* and at the sand-water interface which further enhance microbial removal efficiency (Collins et al., 1992). This diverse ecosystem consists of algae, bacteria, protozoa, and small invertebrates, which are both free and attached to biofilm communities that form on the surfaces of the *schmutzdecke* and sand grains. Initial ripening time of a new slow sand filter is approximately 1-3 weeks (Huisman and Wood, 1974).

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[7] For consistency the following definitions will be used in throughout this thesis:
Schmutzdecke[7] or filter cake - the inert layer of settled particles above the sand media
Biologically active zone - the biological growth within the filter bed
Biofilm - the sticky gelatinous film on the surfaces of the *schmutzdecke* and sand grains

As would be expected, there is a strong positive correlation between the age of the *schmutzdecke* and its bacterial or biomass content (Collins, 1992). Greater influent particle concentration also has been shown to result in quicker biological growth and, thus, increased *E. coli* removal (Weber-Shirk and Dick, 1997). Therefore, filter ripening, a combination of *Schmutzdecke* development and filter biological aging, is a function raw water turbidity and biological content, in addition to time following initial startup.

Filter re-ripening occurs following cleaning or any other disruption to affecting the *schmutzdecke* and filter biological activity. Cleaning of slow sand filters consists of either scraping and disposal of the top few centimeters of sand or "filter harrowing." Filter harrowing is a process by which the settled particles of the *schmutzdecke* are resuspended, and turbid water is replaced with clean water (Collins, 1991). In filter harrowing, part of the biological population of the sand bed is preserved, and thus, re-ripening time is less than that required following scraping (Collins, 1991). The general practice in continuous slow sand filters is to redirect flow to an alternate sand bed following cleaning. This allows sufficient time for filter re-ripening to occur while not compromising effluent water quality.

3.2.2 Physical-chemical mechanisms

The physical, chemical, and biological factors that affect the transport of microorganisms in groundwater are the same factors that affect removal efficiency in slow sand filters. In contrast to the natural variability of groundwater aquifers, process variables of slow sand filters can be manipulated and controlled to maximize the removal of viral, bacterial, and protozoan pathogens. In slow sand filtration, primarily physical-chemical mechanisms of straining and attachment to media or previously removed particles are responsible for the removal of particles greater than 2um in diameter (Weber-Shirk and Richard Dick, 1997a). Biological mechanisms together with physical-chemical mechanisms result in removal of particles smaller than 2um in diameter (Weber-Shirk and Richard Dick, 1997b). Thus, larger protozoan pathogens are removed primarily by physical-chemical means and do not necessitate a biologically mature filter.

3.2.3 Biological removal mechanisms

Bellamy et al. (1985a) among many others have demonstrated that there is "unmistakable influence of biological activity on filter performance" and that nutrients can be added to enhance removal of total coliform. They observed a 60% removal of total coliform with no biological community present, a 97% removal in their "natural" control, and a 99.9% removal when nutrients were added.[8] It was further demonstrated that increased influent bacteria concentrations result in both increased removal and increased effluent concentration. This would seem to indicate that the internal biopopulation of the sand bed metabolizes the influent microorganisms until its capacity is exceeded (Bellamy, 1985b).

[8] Jellison et al. (2000) identified synthetic polymer Pol-E-Z 652 as a specific ripening agent ideal for use in slow sand filters.

Weber-Shirk and Dick (1998) recently found that bacterivory or consumption of bacteria by predators dominates biological activity in slow sand filters while biological removal by the biofilm is not significant. These results indicate that the maintenance of a predatory protozoa population such as a chrysophyte identified by Weber Shirk and Dick (1998) is essential for maintaining removal efficiency. This knowledge is especially critical when considering modification of the well-studied and tested continuous slow sand filter design. Essential mechanisms must be maintained or enhanced in any new application.

3.3 Process and design variables

Because slow sand filtration technology has been in use since the beginning of the 19th century, key design variables were optimized prior to understanding the removal mechanisms discussed in the previous two sections. These design variables (Bellamy, 1985b) include:

- Hydraulic loading rate
- Sand size
- Sand bed depth
- Temperature
- *Schmutzdecke* development
- Filter biological aging

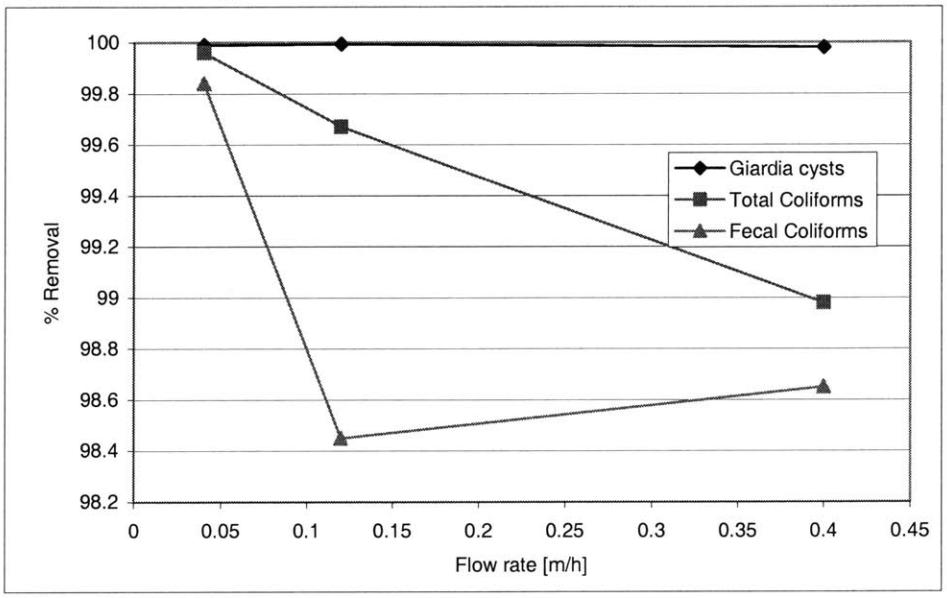
Because of the thoroughness of two studies on microbial removal efficiency by Bellamy et al (1985a, 1985b), their conclusions will be briefly presented to represent industry standards. Bellamy et al. found that while total coliform may be sensitive to process variable changes, *Giardia* (99.92-99.99%) removal does not depend on flow rate (0.04-0.40 m/h) (Figure 3.1), sand bed depth (0.48-0.97m), effective sand size diameter (0.28-0.615mm), or temperature variation (5-14°C). While total coliform does vary slightly with these parameters, sand bed depth, effective sand size diameter, and temperature can be optimized to 0.97m, 0.28mm, and 17°C, respectively.[9] An almost linear decline in total coliform removal efficiency from 99.96-98.98% (Figure 3.1) and an almost exponential decline in standard plate count bacteria removal is observed to be a function of increasing flow rate from 0.04-0.4m/h.

As was discussed in Section 3.2, *schmutzdecke* development is a function of influent water turbidity, which settles at the sand-water interface, and filter biological aging is a function the microorganisms present in raw water. These two parameters will vary based upon raw water source, time following installation, and the other four design variables (hydraulic loading rate, sand size, sand bed depth, and temperature). For example, as the

[9] Total coliform removal was shown to not be sensitive to sand bed depths. Removal improved from 96.0 to 98.6 to 99.4% for effective sand sizes of 0.615, 0.278, and 0.128 respectively. Additionally, Bellamy et al. (1985b) showed 87% removal of total coliform at 5°C and 97% removal at 17°C.

flow rate increases, fewer convected bacteria (present in influent water) will attach to the sand media and, thus, filter biological aging will be effected. As sand size gets smaller, more particles will be trapped at the sand-water interface resulting in faster *schmutzdecke* development. This will, in turn, provide added resistance to inflowing water and result in system head loss and slower flow.

Figure 3.1: Average % removal in slow sand filter columns (Bellamy, 1985a)



4 Intermittently operated house-hold slow sand filtration

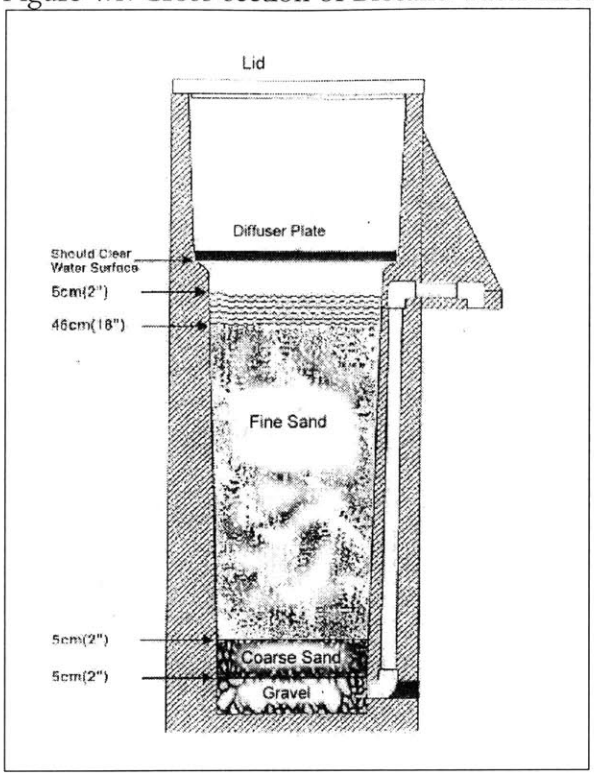
While research has been done to determine transport and biological activity in groundwater and continuous slow sand filters, only one Masters thesis (Buzanis, 1996) and journal paper (Palmateer et al., 1999) have been written on intermittent slow sand filtration, its performance, and design variables. Having overviewed the many biotic and abiotic variables of continuous slow sand filtration in Chapter 3, this chapter will focus on the differences between continuous and intermittent designs. Intermittent use of the slow sand filter depends on the diffusion of oxygen to the sand-water interface during pause time where this oxygen supports the respiration of microorganisms such as predatory protozoa which have been identified as key to biological removal. Designed by Dr. David Manz while at the University of Calgary, the Biosand water filter has undergone several design modifications and iterations to become the robust, intermittently operated filter that it is today. The purpose of this section is to give a brief history of the Biosand filter, overview specific design variables of intermittent, small-scale slow sand filtration, summarize knowledge gained by the iterative design process of the Biosand filter, and outline ideal conditions for the Biosand filter's implementation in developing countries. Key design modifications developed by Dr. Manz to be addressed in the following analysis include scaling down large slow sand filtration, a faster flow rate, intermittent operation, and technology transfer to developing countries.

4.1 Brief history of Biosand filter

Under the guidance of Dr. Manz, an undergraduate researcher David Lee constructed the first intermittently operated slow sand filter in 1991 from a plastic garbage pail (Buzanis, 1995). After many design improvements and laboratory tests performed by Dr. Manz while he was a professor at the University of Calgary, the current plastic and concrete Biosand filter design includes a diffuser basin and a PVC pipe outlet for water level control as shown in Figure 4.1. Water is simply poured in the top of the filter and microbial contamination removed as it flows through sand media and the *schmutzdecke* that forms at the sand-water interface (just as it does in continuous slow sand filtration).

Motivated by development work in South Africa and the Philippines, Dr. Manz began his design process with the objective of creating an appropriate, easily transferable water treatment technology for developing countries. Never losing sight of this objective, Dr Manz has adapted the Biosand water filter to meet developing country needs with emphasize on filter construction and maintenance by local people with available materials.

Figure 4.1: Cross-section of Biosand water filter



In October 2002, Davnor Water Treatment Technologies, the for profit company owned and operated by Dr. Manz, created the non-profit Centre for Affordable Water and Sanitation Technology (CAWST) to offer the humanitarian services Davnor had previously provided. With Dr. Manz holding the patent rights for the concrete humanitarian filter, this technology is distributed freely to developing countries. CAWST supplies technical advice and training services in water and sanitation to local and international NGOs, non-profits, schools, individuals, and all others who wish to implement or improve Biosand water filter projects. Biosand water filter instructor's courses are held at Calgary-based CAWST as well as in countries such as the Dominican Republic where Biosand projects are already underway. Due to the over 20,000 Biosand filters worldwide in more than 30 developing countries, CAWST commonly functions to train the trainers. Samaritan's Purse[10] is a large international Christian aid agency that disseminates Biosand filter technology in many developing countries including Nepal and Cambodia. For example, in Cambodia, Samaritan's Purse trained a local NGO, Asian Outreach Cambodia (AOC), who themselves hold free training seminars on "How to Construct a Water Filter" regularly.[11]

Offered based upon demand, CAWST's 4-day Biosand filter courses educate participants in filtration theory and in the hands-on building of both the plastic and concrete Biosand filters. Courses typically include discussion of water treatment background, technology comparison, water source selection, water epidemiology, laboratory testing, and project

[10] www.samaritanspurse.org
[11] http://www.skyboom.com/aocambodia/ BWF.htm

implementation. All necessary Biosand filter components are built (diffuser, media sieves, lid), concrete is mixed and poured into steel mold, and media prepared in a setting similar to that of developing countries. Filters are also commissioned, operated, and maintenance (such as cleaning) practiced. The ability to simplify otherwise complex design specifications is possibly the greatest accomplishment of Dr. Manz's Biosand filter work. It will be discussed in detail in section 4.5, following a review of more tangible design modifications.

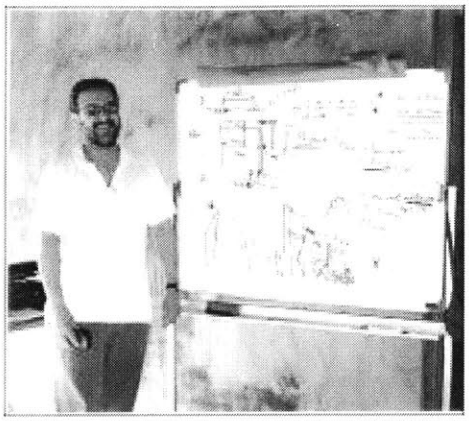


Figure 4.2: Dr. Manz providing Biosand guidance (CAWST, 2002)

4.2 Scaled down for household use

As mentioned previously, all the removal processes inherent to continuous slow sand filtration are also relevant to intermittently operated systems while water is flowing through them. Key parameters to be considered when scaling down large slow sand filtration facilities are:

- Sand bed surface area
- Sand bed depth
- Sand bed surface area to perimeter ratio
- Sand diameter and uniformity coefficient
- Biolayer protection
- Cleaning procedure
- Environmental physical parameters (temperature, turbidity, pH)
- Raw water quality

As mentioned, the Biosand water filter cleaning method is a simple scaled-down version of filter harrowing. Rapid regrowth of the biolayer following cleaning is essential for household slow sand filters as there is no alternative sand bed to which flow can be diverted. Sand size is chosen based on a balance between small sand that will clog frequently if filtered material permeates too deeply (0.5-2cm) and large sand that will require a sufficiently deep filter bed so as to provide adequate opportunity for pathogen capture. This is especially relevant when scaling down filters due to spatial and seasonal variation in raw water quality. Because there is sometimes short-circuiting around filter

sides, it is best to strive for a large surface area to perimeter ratio (or large sand beds). In the Biosand filter, a diffuser basin is used to maintain the integrity of the biolayer and prevent short-circuiting at all locations. Larger sand bed surface area allows for treatment of more water. Thus, higher flow rates are required for the small surface areas of household size filters.

4.3 Faster flow rate

For the reasons described above, the Biosand filter flow rate (0.6 m/hr) is quite high compared to that of other slow sand filters (0.1 m/hr). During continuous flow, the flow rate must be slow enough to allow biofilm growth and limit the shear stress due to inflowing water, yet fast enough to supply 3mg/l dissolved oxygen to the biologically active zone during operation. Bellamy et al. (1985a) observed the removal of fecal coliform to drop from 99.8% to 98.6% as flow rate increased from 0.1 m/hr to 0.4 m/hr. While this decline in removal efficiency may seem insignificant, in scaled-down systems inefficiencies induced by high flow rates may be amplified by other variables that can be controlled. In addition, the depth of the biologically active zone is a function of sand size, flow rate, and raw water quality. If the flow rate is increased, the biologically active zone will be deeper and the breakthrough of pathogens more likely.

4.4 Intermittently operated

The most important modification to traditional slow sand filtration is that the Biosand filter can be operated intermittently based upon demand for water. In developing countries, many people are serviced by either an intermittent supply of water via a distribution system or collect their water in standpipes, springs, wells, or surface water sources. The Biosand filter's PVC pipe outflow maintains a 5-cm standing water headspace above the fine sand media which allows for the diffusion of oxygen from the air to the sand water interface during pause time. While most physical-chemical interactions should remain relatively constant, the biological activity of slow sand filtration is greatly altered by its intermittent use. Similar to those who first used continuous slow sand filtration without knowing why it worked, little currently is known of the biological processes of the Biosand filter. The success of the Biosand filter, rather, is attributable to its performance. Buzanis (1995), a Master's student of Dr. Manz, studied the effect of pause time and depth of water over the sand bed on removal efficiency. His findings include the following:

- Depth of sand layer does not alter removal efficiency
- Depth of biological layer is a function of depth of water over sand bed
- Filters with 2.5cm and 5cm headspaces as opposed to those with 12.5cm give higher removal rates
- Removal efficiency dip is associated with water occupying the biological layer during the pause time
- Hydraulic conductivity in the biologically active zone increases during pause time

These conclusions confirm the hypothesis that oxygen limits biological activity. As dissolved organic matter is consumed during pause time, pore spaces become larger and the transport potential for contaminants in that region increases. There is great opportunity for many interesting laboratory and field studies on the effect of pause time on the removal of contaminants. Also, of particular interest is the time necessary for the establishment of a biological community conducive to high removal efficiency following installation and cleaning. While these parameters have been estimated by CAWST in controlled laboratory studies, they will vary based on raw water source, sand quality, temperature and many other location-specific parameters.

4.5 Project implementation in developing countries

Making a technology accessible to those with a variety of backgrounds is probably more challenging than all the design modifications mentioned above. When taking a technology with proven laboratory success into diverse locations, reproducibility of design is essential for quality control. Biosand filter programs can be divided into three essential phases:

1) Initial project development
2) Filter building, installation, and education of users
3) Performance evaluation and program maintenance

From an economic perspective, implementing a new Biosand filter project requires both an initial capital investment in a steel mold, workshop area, and tools (project development costs) in addition to filter costs for materials, labor, transport, and maintenance. For the real cost of a Biosand filter to be estimated, project development costs would have to be added to filter costs. However, with initial investment from an outside organization or individual, the cost of each Biosand filter would be reduced to just that of materials, labor, and transport. Project development costs will be identified and discussed separately from filter costs so as to determine to what extent donors are needed. Next, the process of building and installing Biosand filters will be explained. Finally, the steps that are necessary to promote local sustainability and economic viability such as education of users, performance evaluation, and program maintenance will be outlined based on a pilot study in Lumbini, Nepal and will be discussed in the Methodology or Results sections of this thesis, as appropriate.

4.5.1 Initial project development

- *Partnership between local NGO, artesian, or entrepreneur and investor, aid organization, or academic institution*
- *Establish organizational structure and become educated in basic concepts of Biosand filter program and technology*
- *Secure Biosand filter workspace and fabricate steel mold*
- *Locate and test good source of sand*
- *Locate source of other component parts (concrete, PVC pipe, gravel)*

Partnership between local NGO, artesian, or entrepreneur and investor, aid organization, or academic institution

The beauty of the Biosand filter concrete design as developed by Dr. David Manz is in its reproducibility, ease of technology transfer, and thus insurance of quality control in remote regions of the world. This solves many logistical problems and allows for partnership with local non-government organizations (NGOs), artisans, or existing businesses (possibly a concrete company). Although a representative from the Canadian International Development Agency (CIDA) reported Biosand filters being used 6 to 7 years after being installed,[12] partnerships will ultimately determine the success, sustainability, and expansion of Biosand filter programs. Because of their skills, commitment, location, and relationships, local NGOs are a logical choice. One somewhat complex partnership began in the Dominican Republic in October of 2000 when Dr. Manz trained 14 Dominicans in filter construction. The program became a combined venture between Rotary Clubs, the Canadian Embassy, and various Dominican NGOs.[13]

Establish organizational structure and become educated in basic concepts of Biosand filter program and technology

After a partnership has been established, the in-country organization must be trained to build, commission, and monitor performance of filters as well as educate users in proper filter maintenance. Existing educational systems such as schools, health clinics, or community meetings could be utilized as avenues for teaching Biosand filter basics, in addition to hygiene and sanitation education already underway, in order to best reduce the incidence of waterborne disease. Another key component to project success is establishing an organizational structure early on. Who will be responsible for filter construction, transport, and installation? If an outside contractor is paid for this service (eg. Durga Ale of Nawalparasi District paid by IBS of Lumbini District in Nepal) and more sand is needed or a diffuser basin breaks, who will be contacted? In other words, how will the systems be maintained? How will the initial start-up be funded, if not by the users? How will the filters be monitored to ensure quality control? While there are many solutions to each of these mentioned questions, each must be addressed and considered in context.

Secure Biosand filter workspace and fabricate steel mold

In order to set up a workshop capable of producing 1 Biosand filter per day you, one needs to locate a space for a workshop and a nearby clean water source. Additionally, a steel mold needs to either be built in-country or shipped to the country, tools need to be bought, and sieve sets for sifting sand need to be built. The steel mold, itself, is the largest single cost when implementing a new project. Davnor, Samaritan's Purse, and the IDRC (IDRC Module 5, 1998) all have available the details necessary for constructing a steel mold which is often more economical then having one shipped due to its ~500lb weight. The filter tool kit must contain all items necessary to construct filters including tools to make sieve sets to prepare media, diffuser basins, lids, as well as those for building the concrete filters themselves. For purposes of differentiating between initial

[12] http://www.acdi-cida.gc.ca/cida_ind.nsf by David Oke

[13] http://www.addyourlight.org/project_biosand.htm

project development and filter operation and maintenance costs, materials for one-time purchase only and their function are summarized in Table 4.1 below:

Table 4.1: Tools necessary for Biosand filter workshop

	Item	Function
	For steel mold (after mold has been built):	
1	Bolt bucket	To hold bolts
2	Large wrench*	To open and close mold when concrete is poured/hardened
3	Smaller wrenches*	To open and close mold when concrete is poured/hardened
4	Pliers	To loosen, tighten bolts
5	Wire brush	To clean bolts
6	Rags	To coat steel mold with vegetable oil
7	Wood spacer	To position standpipe
8	Level	To level steel mold on ground before pouring concrete
9	Trowel or wood	For leveling concrete top once poured in mold
10	Rubber hammer	To make sure concrete is in contact with mold
11	Steel or wood rod	To make sure concrete is properly distributed
12	Wheel barrow	For mixing
13	Shovels	For concrete pouring/mixing
	For seive sets, diffuser basins, and lids:	
14	Staples or bent nails	To connect sieve material to wood frame
15	Nails*	For sieve set, lids, diffuser basins
16	Hammer	For sieve set, lids, diffuser basins
17	Sieve materials*	For sieve sets
18	Small carpenter square	For sieve sets
19	Wood	For sieve sets
20	Hand drill and drill bits	For attaching rope handles to sieve sets
21	Nylon rope	For handles on sieve sets
22	Cloth	For diffuser box seal
23	Tin snips	To snip steel sheet if chosen as diffuser material
24	Saw	For cutting sieve set wood
	For PVC pipe	
25	Sand paper	
26	PVC primer and cement	
27	Hack saw	
28	Spare blades	For hack saw
	General	
29	Tool box	
30	Tape measure	
31	Utility Knife	
32	Buckets for washing media	
33	Measuring cup	To calculate flow rate
34	Bleach	For disinfecting PVC pipe and maybe sand

*1 ½ in or 1 5/8 in depending on size of bolts used in steel mold

*¾ in – at least two

*coated 1inch and coated 2 inch

*½ inch (12 mm opening), ¼ inch (6 mm opening), and mosquito netting

*1/4 inch and 1/8 inch

Locate and test good source of sand
Once a workshop complete with tools and built sieve sets is complete, the next step is to find a good source of sand. Quality of sand is of utmost importance. If the sand itself is contaminated, water treatment success is unlikely. Clean, crushed rock free of organic material with jagged edges and non-uniform sizing is the ideal. As explained previously, two common design parameters for slow sand filtration media are a uniformity coefficient[14] of less than 3 and an effective diameter (d_{10}) range of 0.15-0.35 (Sims and Slezak, 1991 in Logsdon). Sieving the correct sand sizes (described later in this section) is only possible if the sand source its non-uniform in size. It is best to avoid beach sand, river sand, and sand from areas used by people or animals.

Apart from looking for crushing operations and avoiding obviously poor sources, it is best to test possible sources for pathogen content before use as filter media. This test can be done by mixing 5grams of sand to 100mL of clean water, waiting 12 hours for equilibration (with mixture covered, indoors, in the shade), and testing decanted water for the chosen indicator species (eg. *E. coli*, fecal coliform). If pathogen concentration is higher than 100 cfu/100ml, there is a problem. (Davnor, 2001) Alternative methods of disinfecting sand have been proposed including disinfection with water mixed with bleaching powder (Shrestha, 2002).

4.5.2 Building Biosand filters
After the workshop space has been established, steel mold built, and sand source located, Biosand filters can now be built and put into operation in households. A cleverly executed project would include a cost analysis of building filters in each village versus transporting them to the site. Materials such as concrete, sand, and PVC pipe are less delicate and easier to transport in their bulk form as compared with their ~90kg concrete filter form. The cost of bringing the steel mold to villages as compared to transporting ready-made concrete filters would vary based on the number of filters to be constructed. Village-based construction also allows for villagers to assist in many parts of the project including sand preparation (drying, sieving, washing), concrete mixing, lid building, and maintenance. A similar approach has been implemented successfully in Cambodia where families contribute one day's labor and $1USD to help pay for their Biosand filter.[15] Sand preparation in the villages should be considered if a clean water source is available. The products in Table 4.2 should be purchased in bulk according to the number of filters being built.

[14]The uniformity coefficient is a ratio calculated as the diameter of the opening that will pass 60 percent (by weight) of the sample (d_{60}) to that which will pass 10% of the sample (d_{10}). This distribution of sizes decreases the porosity of the sand, increasing the surface area per volume and the likelihood of collisions in the top portions of the sand. Uniform sand sizes are not appropriate.
[15] http://www.skyboom.com/aocambodia/BWF.htm

Table 4.2: Filter materials

	Item	Function
1	Food grade vegetable oil	For steel mold
2	PVC pipe (~1m of 1cm diameter)	For standpipe
3	PVC parts (2 elbows and one T per filter	For standpipe
4	Sand	For media
5	Gravel	For media
6	Concrete, plastic, or wood	For diffuser basin
7	Wood	For lid
8	1part cement (~1 bag)	For concrete mixture
9	1 part clean pea gravel	For concrete mixture
10	1 part clean sand	For concrete mixture

The following comments on the three steps involved in the actual building of a Biosand filter are meant to supplement the detailed instructions provided by Samaritan's Purse (Ritenour, 1998) and CAWST (2001). These steps should guide the project phase of filter building:

1) *Mixing and pouring concrete into steel mold*
2) *Media preparation*
3) *Building diffuser basins and lids*

Mixing and pouring concrete into steel mold
Concrete should be mixed in the following proportions: 1 part cement, 1 part sand, 1 part gravel (1.5-2.0cm diameter). PVC standpipe should be prepared according to CAWST details, and concrete poured carefully into the steel mold. Once poured, concrete must be allowed ~20hrs to harden before filter can be removed from the mold, depending on ambient temperature and humidity. This is the limited factor in filter production, and thus one filter can be produced approximately every day, if one steel mold is available.

Media preparation
Media preparation in user villages should be considered if a clean water source is available. The media preparation process consists of drying, sifting, and washing the three sizes of media (gravel, coarse sand, and fine sand). Sand must be dried so that it can be properly sifted through the 12mm, 6mm, and mosquito-netting sieve sets built during the initial project phase. The majority of the filter media is comprised of sand that has been sifted through the mosquito netting. Next, the sand needs to be washed according to a standardized procedure. Washing and sifting sand is a great way to involve those of all ages, but care must be taken to ensure standard washing procedures (6 scoops of sand per wash, 5 rinses per wash, 5 swirls per rinse) to homogenize production of sand. Washing brings silts, clays, and some organic matter into suspension, which can then be decanted. The more the filter media is washed the faster the flow rate due to the absence of small diameter grains (ie. Media become more porous when washed, which means more inter-particle space for flow). The highest loading rate advisable is 600 liters/hr/m^2 or 37.5 L/hr for a 25cm x 25cm concrete Biosand. Following media preparation, the flow rate should be tested within the concrete structure. If the flow rate is not close to the target of 36+-

10L/hr for typical square concrete filter with area of $0.0625m^2$ (Ritenour, 1998), the media should be prepared again as the integrity of the whole system is at risk.

Building diffuser basins and lids
The purpose of the diffuser basin is to protect the biolayer. To best do this, the diffuser must be tight fitting so water does not skirt around the edges of the diffuser and so that the diffuser does not touch the water surface so as to allow for adequate diffusion of oxygen when filter is not being used. Both the Samaritan's Purse manual (Ritenour, 1998) and Lincoln Lee's thesis (Lee, 2001) provide descriptions, photos, and building instructions for diffuser basins made of wood, plastic, and metal. A new concrete design being used in Nepal solves many of the diffuser problems emphasized by Lee (2001).

4.5.3 Commissioning the filter

- If contaminated, disinfect with bleach solution the standpipe, gravel, and possibly media
- Always add sand to water so as to prevent trapping air within sand column
- Flush filter with 30-100L of water until water runs clear.

4.5.4 Education of filter users

A concise list of what should be taught to filter users is presented below based on the Samaritan's Purse manual, the CAWST course, and the author's personal experience participating in a Biosand Filter Pilot Project in Lumbini, Nepal. While difficult to express even in the absence of language and cultural barriers, the importance and function of the Biosand filter's biolayer must be understood by those building, operating, and maintaining filters. If the biolayer's purpose is not respected, many of the following recommendations will not be understood and Biosand filter's technical performance may be compromised. Otherwise infrequent filter cleaning, moving the filter following installation, or keeping the diffuser in place may seem unnecessary. Thus in addition to an explanation deemed to be culturally appropriate; the following points should be emphasized during filter installation:

1) **Filter should not be moved** once sand is in place.

2) **Diffuser plate should be left in place** to best protect biolayer.

3) **Clean** only when flow is not sufficient to meet household needs (when absolutely necessary). The proper cleaning procedure consists of bringing settled solids into suspension by stirring the top 2-3 cm of sand. Dirty water should then be scooped out of headspace and replaced with clear water until water in headspace is itself clear.

4) **Prevent clogging** by allowing source water to settle before feeding the filter. Clogging occurs when water of high turbidity is continually poured into filter. An easy method to minimize influent turbidity is to place cloth inside the diffuser basin to pre-filter out large particulate matter.

5) **Use the highest quality source water available.** Source water with fine silts and other fine particles may prematurely clog the sand column. In addition, since filter removal efficiency is a function of source water, the better the influent water poured into the filter, the better the resulting effluent quality. For example, if two sources of water containing 200cfu/100ml and 20cfu/100ml of fecal coliform, are filtered with 95% removal efficiency, water flowing from the Biosand filter spouts will contain 10 cfu/100ml and 1cfu/100ml of fecal coliform, respectively.

6) **Never block spout of filter** to keep water from draining. Connecting other devices to spout may result in siphoning or draining which is detrimental to the biological community essential for filter performance.

7) **Do not use the filter as storage device**, as it may attract animals.

8) **Incorporate behavior modifications** such as designating buckets as post-filtration and pre-filtration, filtering water immediately before use, and using filtered water for cooking and cleaning, in addition to drinking.

4.5.5 Performance evaluation/ program maintenance

Utilizing existing local organizations and resources, a program to evaluate filter performance and for filter maintenance should be established. This program should include standard protocols for testing the Biosand filter and other household treatment devices in developing countries. Challenges to testing the Biosand filter include effluent quality variation with varying source water which may result in spikes in influent concentrations translating to effluent concentration spikes.

5 Methodology

During January 2002, 8 environmental engineering students from MIT's Masters of Engineering program traveled to Nepal to study point-of-use water treatment. Four students (Morganti, Low, Sullivan, and Lukacs) focused on microbial contamination and its removal on a household-level. Luca Morganti and Chian Siong Low (2002) worked primarily at Environment and Public Health Organization (ENPHO), a Kathmandu-based NGO with a continuous power supply and complete laboratory facilities for incubation, sterilization, and the deionization of water. Hannah Sullivan and the author, Heather Lukacs traveled to the southern Terai region where they were hosted by the International Buddhist Society in the Lumbini township.

5.1 Field site description

This chapter will describe the field microbial analysis of Lukacs and Sullivan in the Lumbini township during January 2002. The aim of such analysis is to demonstrate the validity and reproducibility of such results given the challenges posed by field conditions including an intermittent power supply, villages accessible only by bike or foot, lack of laboratory facilities, and language barriers. All laboratory supplies used by Sullivan and Lukacs were brought from MIT (see Appendix A), purchased in Kathmandu (Methanol, Q water) or bargained for at the local market (pot, stove). The majority of this chapter will focus on the membrane filtration technique (sections 5.3 and 5.4), as this was the first field analysis of its kind performed by the MIT Nepal Water Project. For more information on the H_2S testing methodology, refer to Hannah Sullivan's work (2002). It will just be briefly overviewed in section 5.2.

Field-testing consisted of 109 samples analyzed for H_2S producing bacteria and enumeration of 67 fecal coliform and 23 *E.coli* samples using the membrane filtration technique. Indicator organisms and not the pathogens themselves were measured. This becomes increasingly important the further one gets from the lab where materials can become the limiting factor. All field procedures for sample collection, preservation, preparation, and filtration in addition to media selection, sterilization, and incubation will be discussed. It is hoped that given the detail of this section, future researchers will be able to repeat the strengths of the author's analysis and identify and improve upon insufficiencies.

5.2 Presence/ absence H_2S bacteria tests

These indicator tests are based on the premise that hydrogen sulfide (H2S) producing bacteria are associated with fecal contamination and the presence of coliform bacteria, and thus indicate the presence of waterborne pathogens. The presence/ absence of H_2S bacteria in the Lumbini township was determined using both self-made H_2S tests, based on methodology described by the IRDC[16], and an H_2S test with HACH prepared medium. Samples were collected in 100ml whirl-pack bags and then poured into 10ml glass vials

[16] For more information about these tests including how to prepare the culture medium and sample bottles, see the IDRC module 7 (Revelo, 1998).

for IDRC tests or 20ml glass vials for HACH tests already containing the appropriate medium. The vial was then incubated for 72 hours at 37°C in an Amy Smith phase-change incubator[17] and monitored for color change. If the vial turned from yellow to black (or if a black precipitant formed), it was considered to be positive for H_2S bacteria.

While not described in Standard Methods, the International Development Research Centre (IDRC) of Canada and others have advocated the use of H_2S tests in developing countries as a cost-effective, simple method to monitor drinking water. Given the wide range of incubation temperatures and the low cost of self-made IDRC tests (US$0.13 per test), H_2S tests are ideal for regular water quality monitoring and can help identify contaminated drinking water sources.

5.3 Enumeration of fecal coliform and *E.coli* bacteria

The intent of this section is to first explain the field procedure performed by the author in Lumbini, Nepal during January 2002. Using a membrane filtration technique, fecal coliform bacteria were filtered from water samples on to filter paper, which were then placed in m-FC medium containing lactose, protein digest, vitamins, bile salts, selective chemicals, and aniline blue dye. During incubation at 44.5°C, fecal coliform grow and produce an acid that reacts with aniline dye in medium causing fecal colonies to appear blue while non-fecal coliform colonies turn gray to cream-colored.

5.3.1 Precision

Given the intention to survey all the IBS public wells in 17 different villages over a 2-week time period, breadth was chosen over depth in this study. Triplicate samples using the same membrane filtration apparatus, incubator, and analyst yielded consistent results under simulated field conditions in an MIT laboratory. While in Lumbini, the method used generally involved one sample per well along with one additional sample when dilution seemed necessary[18]. Duplicates of all Mahuwari, Bhagatpurwa, and Shivagadiya samples (18 total) confirmed that results were consistent with the approximate 95% confidence limits for membrane filter coliform results given by Standard Methods (1998) using the following normal distribution equations where c equals the number of coliform colonies counted[19]:

$$\text{Upper limit} = c + 2\sqrt{c}$$

$$\text{Lower limit} = c - 2\sqrt{c}$$

In addition, 23 of the 67 fecal coliform samples analyzed were also tested for *E.coli*. The enumeration of different indicators of pathogenic contamination for the same wells lends credibility to media preparation, preservation, and counting of cells.

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[17] Amy Smith of MIT developed a phase-change incubator. When heated in boiling water, this plastic incubator contains a liquid phase-change material that maintains a constant 37°C temperature while cooling.

[18] Samples were diluted when they were visually more turbid, from a relatively new well, or from a well with known contamination

[19] "c" must be greater than 20 organisms to use these limits. If c<20, Table 9222.I on page 9-61 in Standard Methods (1998) provides 95% confidence limits.

5.3.2 Media preparation/ preservation

For fecal coliform analysis, Millipore pre-made m-FC with rosilic acid broth in 2ml plastic ampoules was used. Brought from the United States, these ampoules were kept within the advised temperature range by carrying them onto flights in a hand-held cooler (despite many checks and airport security) and by placing them a in cool water bath or a refrigerator when available.

A powder media prepared by BD/Difco, Bacto EC Medium with MUG, was used for *E. coli* analysis. Pre-weighed in the US, this medium was brought to Lumbini in 20ml sterilized glass vials. Prior to use, a batch of liquid medium was prepared by pipetting the correct amount of water into the glass vials, heating it briefly in a bath of boiling water to dissolve colloids, and then sterilizing it in the water bath for 20 minutes. Following preparation, it was refrigerated along with the fecal coliform media when not being used.

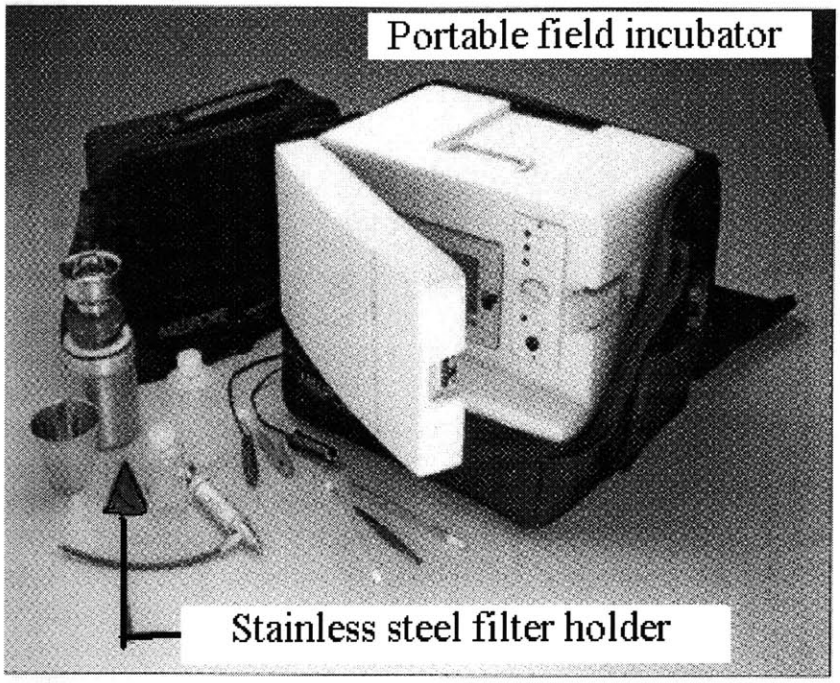
5.3.3 Sample collection/ preservation

Samples were collected from wells, from Biosand filter spouts, and from household buckets directly into 100ml pre-sterilized whirl-pack bags in the 17 village field sites. Samples were transported from villages in an insulated cooler bag for same-day analysis upon return to the International Buddhist Society. Samples from the same whirl-pack bag were used for both H_2S and fecal coliform tests. Effort was made to minimize the time between sample collection and analysis. When travel to village by Jeep was possible, there was minimal delay (.5-4 hours) between sample collection and analysis. When villages were accessed by bike, there was an additional 1-2 hour delay, on average, before analysis.

5.3.4 Membrane filtration

Samples were shaken and poured from whirl-pack bags into a graduated cylinder. The known sample volume was then poured into a Millipore stainless steel field filter holder (Figure 5.1) serving to filter samples through a 47 um pore space paper. A hand pump created the vacuum. Following filtration, the funnel was rinsed with a consistent amount of Q-water (to capture bacteria stuck to funnel) and filter paper placed in a disposable plastic petri dish already containing prepared medium and an absorbent pad.

Figure 5.1: Field incubator and membrane filter



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5.3.5 Incubation

Once all daily samples were filtered, they were placed together into a Millipore portable field incubator (Figure 5.1) and incubated for 24 hours at 44.5°C. The incubator was primarily powered by the intermittent power supply. During hours of peak electricity demand (during the evening), there was frequently insufficient power transmission to the incubator. During these times and any other time the incubator's low power light shined, 12-volt nickel cadmium batteries were used to power the incubator. Following incubation, plates were removed from the incubator and counts recorded.

5.3.6 Sterilization

Pre-sterilized plastic pipette tips, whirlpack bags, fecal coliform media, culture plates, and filter pads brought from the United States to Nepal in the author's luggage were all used. All surfaces were cleaned with methanol, obtained in Kathmandu and brought to Lumbini, before and periodically during laboratory analysis. Glass graduated cylinders (used to measure the sample volume to filter) were sterilized by boiling in water for approximately 10 minutes in accordance with the Millipore field manual (Millipore, 1992). Creating formaldehyde as a byproduct, methanol was ignited to sanitize the stainless steel field filter holder shown in Figure 5.1. As recommended by Millipore, methanol was given sufficient contact time (10-15 minutes) with the stainless-steel filter to allow for disinfection.

5.4 Keys to membrane filtration success in Lumbini, Nepal

While the author's field analysis proved successful, challenges and time constraints could be easily minimized. While not novel ideas, the following methodology modifications are intended to assist future MIT Masters of Engineering students or others in field studies in

remote locations such as Lumbini, Nepal based upon resources (including time) available.

Keep samples cool between sampling and analysis
It is understood that samples should be filtered as soon as possible following collection. The US EPA recommends filtration and beginning incubation in the field when there will be more than a 6 hour delay between sampling and processing. The IDRC confirms this 6-hour lag-time upper limit for unrefrigerated samples, but allows up to 30 hours if samples are refrigerated (or placed in a cool container of insulating material containing ice).[20] Millipore, on the other hand, suggests either a maximum delay between sample collection and processing of 6 hours for samples refrigerated at 10°C or 1 hour for unrefrigerated samples. In the case of Lumbini, care needs to be taken to keep samples cool while in the field due to the distance between field locations and the warm climate (especially during summer months). An insulated bag preferably with ice would be the minimum.

Minimize sterilization
Samples collected in 100ml whirl-pack bags can be poured directly into filtration apparatus. This will eliminate the need to sterilize glass-graduated cylinders in boiling water and will, thus, reduce possible contamination risk, sterilization time, and fuel usage.

Decrease time between analysis (filtration) and incubation
A field filtration unit with a disposable funnel can be used to greatly reduce filtration time. Up to 15 samples can be analyzed in around 30 minutes as compared to ~3 hours with the stainless steel filtration[21]. In addition to freeing up time for other pertinent activities, when analyzing for fecal coliform or *E.coli*, all prepared cultures should be placed in incubator within 30 minutes following filtration to ensure the heat shock of non-fecal coliform organisms. In addition to time and accuracy advantages, use of disposable funnels minimizes the Q water necessary for rinsing the stainless steel filters following formaldehyde sterilization. When all Q water must be transported to villages and many samples are to be run, this becomes increasingly important.

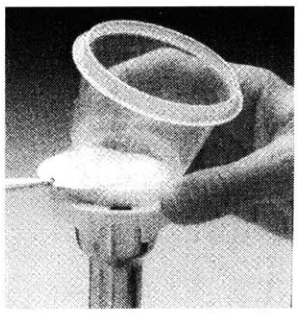

Figure 5.2: Membrane filter with disposable funnel

[20] The IDRC recommendations apply specifically to H_2S tests while the others apply to all microbial field testing including P/A and membrane filtration.
[21] This is based on the author's personal experience in Nepal and Boston.

Difficult to use powder media in field
Proper sterilization of powder media is difficult, if not impossible under field conditions. Because media prepared from powder must be used within a few days, media must be made frequently during extended field-testing. Every time media is extracted via pipette from its bottle, there is risk of contamination. Additionally, these broths grow cultures that are more difficult to count following incubation than their liquid counterparts (such as m-FC or m-ColiBlue24 broths). Since the function of media is to grow bacteria, extreme care must be given to ensure its sterility and consistency. For this reason, it is concluded that media prepared in the field from powder should only be used when it has been proven to perform as well as quality-tested media. As documented extensively by Low (2002), it is difficult to compare different media even when they test for the same indicator organism.

Simultaneous detection of E.coli and total coliform preferred
The choice of indicator species should be made carefully. Field options for membrane filtration analysis include fecal coliform, *E.coli*, and total coliform. M-Coliblue24 broth can simultaneously detect total coliform and *E.coli* following incubation at 35°C for 24 hours. In this medium, colonies of non-fecal coliforms reduce TTC (2,3,5 triphenyltetrazolium chloride) in the medium causing them to turn red. *E. coli*, on the other hand, turn blue due to a reaction between the enzyme beta-glucuronidase and BCIG (5-bromo-4-chloro-3indolyl-beta-D-glucuronide). This difference in colony color allows for the precise differentiation between of *E. coli* and non-fecal coliforms. (HACH, 2001) Therefore, heat shock (required to kill non-fecal coliform when using other fecal coliform or E.coli broths) is unnecessary when using m-Coliblue24. While mColiBlue24 broth is costly when compared to powder media or P/A tests, its cost of ~$1.50 per test is comparable to the $0.95 per fecal coliform test using m-FC broth,[22] especially when considering that two indicators are examined. For a comprehensive review of membrane filtration options appropriate for lab and field options in Nepal, see Low (2002).

Incubate at 37 ℃
Incubating in a controlled environment with very slight variation is important for microbial analysis. Two possibilities for field incubation exist. One is a phase-change incubator developed by Amy Smith of MIT. This incubator is heated in boiling water and maintains a constant 37°C temperature while cooling. The other, more traditional, option is a field incubator that runs on electricity or from 12V rechargeable batteries. While the electric-incubator is necessary for tests that require the higher incubation temperature of 44.5°C (fecal coliform and *E.coli*), the phase-change incubator offers an alternative for tests at 37°C. When the power supply is intermittent, incubators must be battery powered to maintain the precise temperatures necessary to select for indicator organisms. This will help secure sample quality from unplanned power outages and low levels of power transmission during peak evening hours.

[22] HACH company (2001) Products for Analysis. p. 143

5.5 Methodology summary

In sum, many of the challenges experienced by the author when using membrane filtration in the field can be easily avoided by the use of m-ColiBlue broth, an incubator operated by batteries only, and a filtration assembly with a disposable funnel. Still, there are unavoidable risks associated with membrane filtration including the importance of refrigerating broth both during transit and at the field site and the relatively high cost of analysis. The advantages of membrane filtration relative to most probable number (MPN) and P/A analysis include the shorter 24-hour incubation time required (rather than 48-96 hours) and a superior sensitivity of 1 CFU/ 100ml[23]. This is in addition to the obvious advantage of more precise, reproducible results. The difference between wells contaminated with 5 cfu/100ml and 500cfu/100ml will undoubtedly dictate different point-of-use water treatment interventions.

[23] This assumes P/A tests of sample volumes <100ml. Sensitivity of 10ml tests = 10cfu/100ml and sensitivity of 20ml tests = 5 cfu/100ml.

6 Results and project implementation

6.1 Lumbini background

Located 10 kilometers from the Indian border in Nepal's southern Terai region, Lumbini, Nepal is similar geologically and culturally to India. Bordered to the north by the Himalayan foothills and to the south by the Ganges River, the Terai's climate is subtropical with average minimum and maximum winter temperatures of 7°C to 23°C respectively. Land that was once lushly covered with tropical vegetation is now primarily agricultural dictating the lifestyle of its inhabitants.[24] The majority of precipitation falls in the Terai during the summer from May to October. During this rainy season, insect populations and waterborne pathogens that transmit diseases like malaria and dysentery, respectively, flourish. (Maitri, 2002)

6.1.1 International Buddhist Society (IBS)

In addition to being home to the Tharu people, one of the oldest groups native to the region, Lumbini is where Siddhartha Gautam (Buddha) was born in about 543 B.C. Many temples have been constructed in close proximity to the Sacred Garden, birthplace of Siddhartha and the religion he founded, Buddhism. Fast forwarding two and a half millennia later, the Nepalese monk, Bhikkhu Maitri, founded the International Buddhist Society (IBS) in August 1993 with a two-fold complimentary purpose of serving local people and acting as a center for Buddhist activity. Stated objectives of IBS are:

- To provide free medical treatment to the poor people of the villages of the district
- To establish an information center for foreign visitors
- To establish a library for the education and dissemination of Buddhism among the local people
- To construct and provide a rest home for pilgrims

The "poor people" identified above live in small agrarian communities scattered around the Lumbini[25] township in the Rupendehi District. Many of these villages are only accessible by foot, bike, or tractor during the dry season. During the monsoon season, difficult walking and even fording of rivers is, at times, the only way of travel to and from these villages. (Maitri, 2002) IBS chose 17 villages as target populations to serve. These villages have populations ranging from 100-1000 people with 73% and 40% of the boys and girls, respectively, age 5-15 attending school. Schools range from village-level gatherings of children of all ages with one instructor to schools that draw children from several villages. In these IBS villages, 64% of men and 10% of women over the age of 15 are literate. (IBS, 2002) A variety of native languages are spoken complicating communication even between Nepali speakers and local villagers. It should be noted that

[24] http://www.geographia.com/nepal/

[25] In this report, the township where the International Buddhist Society and Sacred Garden are located is called Lumbini for simplicity. According to Mallik (2000), the township is actually called Buddhanagar, the Village Development Community (VDC) is Lumbini Adarsha, and the zone (which comprises several districts including Nawalparasi and Kapilvastu) is Lumbini.

Nepali is the second language for most of the Nepalese including those who live in the Katmandu valley.[26]

6.1.2 Outside investors

Since 1993, IBS has expanded from a free health clinic run by Dr. Narendra Mallik in Lumbini to include an integrated community health and empowerment program in 17 villages surrounding Lumbini. With financial assistance from Exchange Himalayan of France in 1996, programs continued to expand (Mallik, 2000). After Dr. Mallik connected villager sickness to waterborne pathogens, IBS health programs began to incorporate source water provision. In June 2000, IBS partnered with Cross Flow Nepal Trust[27] to address the prevalence of waterborne disease (Table 6.10). Cross Flow, a UK based organization, currently employs 15 Nepalese staff including 7 women "motivators" who spend their days, according to Cross Flow, "cycling to the villages, identifying people's needs, and giving them help and hope." Women motivators are trained in assessing health problems and report field observations to Dr. Mallik following visits to village homes and schools. They also educate villagers on proper health, water, and sanitation practices and encourage the use of deep tube wells (>150 feet deep) installed by IBS/Cross Flow. Cross Flow share IBS's health mission recognizing the lack of safe drinking water, toilets, latrines, irrigation system as well as the prevalent unemployment in the surrounding villages. Cross Flow aims to hand their program over entirely to local institutions, preferably of a village level, within 5 years.

To date, the International Buddhist Society and their partnering organizations have installed or are in the process of installing 57 hand pump tubewells in the 17 chosen villages (Table 6.1), with plans to expand their projects to 5 additional villages in 2002. These tubewells are dug with manual power and are generally from 180 to 200 feet in depth. In 13 of the 17 villages, anywhere from 50 to 175 meters of earthen open drainage channels are currently being installed to drain flow from new and existing tubewells. While little has been done to improve the nonexistent sanitation in the villages (there is only one latrine for nearly 10,000 people in the 17 villages), funding for the construction costs of 6 latrines has been secured.

In addition, IBS with assistance of Lee Hersh and Susan Murcott, initiated the Lumbini Household Chlorination Study in January 2001 based upon CDC's Safe Water System (as described in Chapter 2) and the Lumbini Biosand Filter Pilot Project in January 2002. The objective of these two pilot projects is to reduce the incidence of waterborne disease by improving the water quality in village homes. In addition, it is hoped that by providing a safe water source to households, IBS's current health and hygiene education program will become more effective.

While levels of waterborne disease have dropped in many of the villages, seasonal fluctuations in health are still observed. Several groups of researchers have vicited Lumbini to test drinking water sources and to evaluate the feasibility of point-of-use

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[26] There are at least 120 different living languages spoken in Nepal. http://www.ethnologue.com/show_country.asp?name=Nepal

[27] www.crossflownepal.org

water treatment technologies such as solar disinfection, chlorination, and slow sand filtration. Hannah Sullivan and the author conducted the most recent fieldwork in January 2002 consisting of both an extensive survey of all IBS wells in the 17 villages as well as an evaluation of a chlorination pilot study and the Biosand Filter Pilot Project. Well survey results and the Biosand Filter Pilot Project results and observations will be presented in Sections 6.2 and 6.3, respectively.

Table 6.1: Villages targeted by International Buddhist Society health outreach (IBS, 2002)

	Village	Population	IBS wells[a]	# People per well	Date visited[b]
	Lumbini				1/3/02-1/18/02
1	Lankapur	157	2	79	1/14/02
2	Mahuwari	644	5	129	1/13/02
3	Khambe	445	3	148	1/9/02
4	Laximapur	382	4	96	1/18/02
5	Mahilwari	730	4	183	1/17/02
6	Dhodahawa	544	2[c]	272	1/10/02
7	Sujandihawa	896	3	299	1/14/02
8	Ramuwapur - Ten	595	3	198	1/11/02
9	Sonbarshi	251	4	63	1/11/02
10	Ramuwapur - Khu	373	2	187	1/14/02
11	Sonbarsha	804	3	268	1/11/02
12	Bhagatpurwa	310	4	78	1/13/02
13	Shivagadiya	426	3	142	1/13/02
14	Sekhuwadand	213	2	107	1/14/02
15	Mujahana	689	4	172	1/18/02
16	Bhagawanpur	975	4	244	1/9/02
17	Lamtihawa	893	5	179	1/8/02
	Total/Average	9327	57	167	

[a]There is an additonal artesian well installed by IBS in Dhodahawa

[b]These wells were visted by Hannah Sullivan and Heather Lukacs

[c]These wells are existing, proposed, or currently under construction by IBS/ Cross Flow Nepal as of January 2002

6.2 Lumbini well survey results

In this section, all the data available on wells tested in IBS villages from 1999-2002 will be presented. Before presenting actual results, it is important to note the difference in the testing methodology used. In these studies, total and fecal coliform, *E.coli*, and H_2S producing bacteria were used to indicate the presence of pathogens in village water sources. When comparing the data sets below, special attention should be paid to the sensitivity (dictated by sample size)[28], reproducibility, and accuracy of each test. In other words, if wells sampled contain low-level H_2S bacterial contamination, what is the

[28] 20ml HACH test used by both Murcott (2000) and Smith (2001) have detection limits of 5 cfu H_2S/ 100ml while 10ml IDRC tests used by Smith (2001) and Sullivan and Lukacs (2002) have detection limits of 10 cfu H_2S/ 100ml. All membrane filtration test have detection limits of 1-2 cfu/100ml based upon sample volume used and dilution.

likelihood of a positive HACH test outcome with a 20ml sample size? If I measure three samples of the same well water, what is the combined human and analytical error introduced (i.e. Are observed differences "real" or do they lie within procedural noise)? If I measure that same well tomorrow or in an hour, will it yield the same result?

6.2.1 Past work done in Lumbini

6.2.1.1 Peter Moulton well survey/ SODIS introduction (April 1999)

In April 1999, Peter Moulton conducted the first known water quality survey of villages in the IBS program. He also introduced household level solar disinfection to villagers as an alternative to drinking well water directly. His well survey results (Table 6.2) show that open wells and rivers were all quite contaminated with more than 200 and 360 cfu total coliform/100ml, respectively. His well survey also discovered the presence of widespread low level contamination in both shallow and deep tube wells, and that even 22% of deep wells (with depth >150 feet) contained substantial contamination. All 42 of Moulton's well samples were analyzed for presence or absence of H_2S reducing bacteria and for total coliform and *E.coli* using a glass Millipore filter holder, a Millipore hand pump, a 500 ml plastic flask, and a QFC (Good Quality Farms) incubator (Moulton, 2002). Moulton's results obtained from the different indicator tests and analytical tests agreed 80% of the time.

Table 6.2: Wells with total coliform contamination in Lumbini, Nepal (Moulton, 1999)*

Well Type	Depth [ft]	# Wells Tested	>0 cfu/100ml	>10cfu/100ml
Shallow	<60	22	72%	27%
Deep	>150	9	78%	22%
Open	20-30	9	100	100%
All Wells		32	79%	43%

Peter Moulton concluded the following:

- Water quality testing is important and should be continued by setting up village water quality programs using H_2S tests
- Wells should have proper maintenance, sealing, drainage
- Shock chlorination following well drilling should be considered

Due to turbid water sources and higher levels of contamination than anticipated, Moulton suggested slow sand filtration on a community or household scale. He concluded that while SODIS could be used for wells with little contamination or following slow sand filtration, it should not be used alone.

6.2.1.2 Susan Murcott, Lee Hersh, Cliff Hersh well survey (January 2000)

In January of 2000, following the MIT Masters of Engineering field season in Kathmandu, Susan Murcott, Lee Hersh and Cliff Hersh traveled to Lumbini and surveyed 27 wells from 8 Lumbini villages for microbial, turbidity, nitrate, and arsenic

contamination. Using 20ml HACH H_2S tests with improvised incubation,[29] they found that 63% of all wells tested positive (Table 6.3). Deep wells represented in Table 6.3 are those >150 feet deep while shallow wells are <150 feet deep.

Table 6.3: Presence of H_2S producing bacteria in Lumbini, Nepal (Murcott, 2000)

Well Type	Ave Depth [ft]	# Wells Tested	% Positive (HACH)
Shallow	45	14	64%
Deep	200	13	62%
All Wells	127	27	63%

6.2.1.3 Megan Smith / Timothy Harrison well survey (January 2001)

MIT Nepal Water Project Masters of Engineering Student's Megan Smith and Timothy Harrison conducted a 34 well survey of microbial contamination of 7 Lumbini villages in 2001. Table 6.4 presents the results from both 10 ml IDRC H_2S tests and 20ml HACH H_2S tests which have detection limits of 10 and 5 bacteria/ 100ml, respectively. As would be expected, the more sensitive 20ml HACH tests detected more contamination than their 10ml IDRC counterparts. In addition, Smith's 2001 results show that shallow well are 16% more likely to be contaminated than deep wells with depth >150 feet.

Table 6.4: Presence of H_2S producing bacteria in Lumbini, Nepal (Smith, 2001)

Well Type	Ave Depth [ft]	# Wells Tested	% Positive (IDRC)	% Positive (HACH)
Shallow	47	13	46%	69%
Deep	190	16	33%	53%
Open	53	3	100%	100%
All Wells	105	32	44%	63%

6.2.2 Hannah Sullivan / Heather Lukacs well survey (January 2002)

Following the methodology described in Chapter 5 of this thesis, 86 tubewells were tested for H_2S bacteria (10 ml IDRC P/A), 67 wells for fecal coliform, and 23 wells for *E. coli* during January 2002 by MIT Nepal Project students Hannah Sullivan and Heather Lukacs. For the purposed of this analysis, deep, public wells refer primarily those >150 ft that were installed by IBS within the past 4 years.[30]

6.2.2.1 Well survey for H_2S bacteria

Of the 86 wells tested for H_2S bacteria, 80 are represented in the Figure 6.5 below. Five newly installed wells and an open well in Mahuwari were omitted from this initial analysis to best differentiate between tubewell contamination due to installation practices and contamination originating from other sources.

[29] Improvised incubation was performed using an insulated box filled with chemical heating packs from Eastern Mountain Sports.

[30] If comparing this analysis to that of Sullivan (2002), she refers to these deep wells as "public" wells.

Table 6.5:Presence of H2S producing bacteria in Lumbini, Nepal (2002)

Well Type	Ave Depth [ft]	# Wells Tested	% Positive (IDRC)
Shallow	62	31	35%
Deep	184	49	29%
All Wells	137	80	31%

61% of wells tested are deep, public wells while individuals own 39% of the shallow wells. Table 6.6 demonstrates water quality variation between villages and public/private wells within each village. Both public and private wells in Lankapur (#1), for example, show high probability of contamination. Comparative analysis between public and private wells could narrow down possible sources of well contamination. In Lamtihawa (#17), no contamination was found in the 2 private wells while 50% of the 4 public wells were found to be contaminated. One explanation for this would be that private wells tested in Lamtihawa are better maintained than their public counterparts. In this case, cow dung slurry used during well drilling and cow dung used as household building material could be ruled out as sources of long-term contamination since these sources would also have contaminated private wells. More likely sources would be bathing, clothes washing, and dishwashing on community well platforms and the close proximity of animal lodging to tubewells (household wells are often inside houses or protected while public wells are generally accessible by cows and other animals).

Table 6.6: Presence of H_2S producing bacteria in public and private wells by village in 2002

Village	Private		Public	
	# Wells Tested	% Positive	# Wells Tested	% Positive
1 Lankapur	2	100%	5	40%
2 Mahuwari	1	0%	3	0%
3 Khambe	3	33%	2	50%
4 Laximapur	0		4	75%
5 Mahilwari	3	67%	3	33%
6 Dhodahawa	1	100%	2	50%
7 Sujandihawa	0		3	0%
8 Ramuwapur - Ten	1	100%	1	0%
9 Sonbarshi	0		3	0%
10 Ramuwapur - Khu	1	0%	4	50%
11 Sonbarsha	2	0%	2	50%
12 Bhagatpurwa	2	50%	4	0%
13 Shivagadiya	0		2	0%
14 Sekhuwadand	4	25%	0	
15 Mujahana	6	17%	3	33%
16 Bhagawanpur	3	33%	4	0%
17 Lamtihawa	2	0%	4	50%
Total	31	35%	49	29%

Taking this analysis one step further, new data can be placed in the context of past Lumbini well surveys (Table 6.7). This will serve both to determine whether the contamination found by Moulton (1999), Murcott (2000), and Smith (2001) all of which was collected in the dry season (either April or January) is still present in Lumbini villages and will identify the most "dirty" towns in which point-of-use water treatment

technologies should be first introduced. This dry season data is meant to target priority locales for future testing. Because all public wells present in the 17 villages were tested in 2002 while only a small fraction of private wells were tested, Table 6.7 includes only deep, public wells (or those > 150 ft in depth).

Table 6.7: Presence of H_2S producing bacteria in deep wells by village in 2000, 2001, 2002[31]

Village	Murcott 2000		Smith 2001			Sullivan & Lukacs 2002	
	# wells[a]	% positive [20ml HACH]	# wells	% positive [20ml HACH]	% positive [10ml IDRC]	# wells	% positive [10ml IDRC]
Lumbini	1	0%					
1 Lankapur			3	100%	67%	5	40%
2 Mahuwari						3	0%
3 Khambe						2	50%
4 Laximapur						4	75%
5 Mahilwari	1	0%				3	33%
6 Dhodahawa	1	100%	3	67%	33%	2	50%
7 Sujandihawa						3	0%
8 Ramuwapur - Ten	2	50%				1	0%
9 Sonbarshi	4	50%				3	0%
10 Ramuwapur - Khu	1	100%				4	50%
11 Sonbarsha	1	100%	4	25%	25%	2	50%
12 Bhagatpurwa	1	100%	3	33%	0%	4	0%
13 Shivagadiya						2	0%
14 Sekhuwadand							
15 Mujahana						3	33%
16 Bhagawanpur			2	50%	50%	4	0%
17 Lamtihawa						4	50%
Total/Average	12	62%	15	53%	33%	49	29%

[a] Madhuvani primary school was left out of this data set while it was included in Table 6.3

The recent well survey of Sullivan and Lukacs (2002) confirmed the earlier IDRC test results of Smith 2001. Using 10ml IDRC H_2S tests, these surveys showed that 29% and 33% of deep, public wells (those >150 ft in depth) tested positive to H_2S bacteria. While fewer samples were analyzed using 20ml HACH samples, the results of Murcott (2000) and Smith (2001) also show agreement with 62% and 53% of wells testing positive to H_2S bacteria, respectively. Two important conclusions can be drawn from this analysis. The first is that the deep well contamination in IBS villages has not changed over the past three years, and the second is that the 20ml HACH tests with their lower detection limit are almost twice as likely to test positive than the 10ml IDRC tests. This further indicates the prevalence of low-level microbial contamination (<5 cfu/100ml). Again, it should be noted that due to the small number of wells tested and seasonal bias of represented studies, more samples should be taken to confirm and augment those results presented above.

6.2.2.2 Enumeration of fecal coliform well contamination

In addition to the 86 wells tested for H_2S bacteria, 67 wells were tested for fecal coliform using Standard Method's membrane filtration method (Standard Methods, 1998). The intent of performing membrane filtration tests was to quantify contamination in addition

[31] Because Lumbini is not one of the official 17 towns in IBS's health outreach program, it will not be given a number in this analysis.

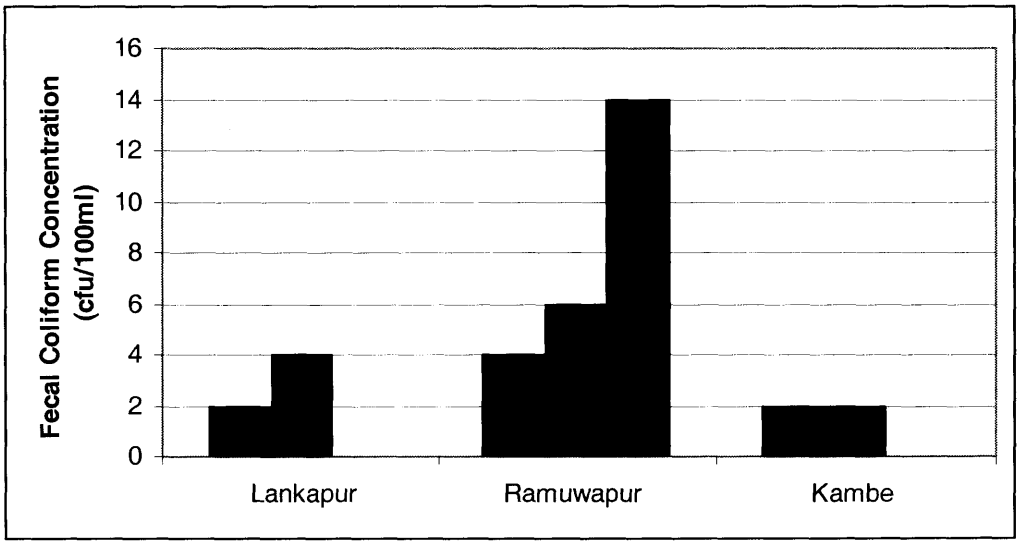
to detecting its presence or absence. Enumeration of coliform bacteria can provide valuable data to assist in future project planning by identifying wells that pose the greatest risk to public health. If serious contamination is discovered, its potential impact can be mitigated. Of the 39 deep public wells tested for fecal coliform contamination, 4 were new wells and highly contaminated (Figure 6.1). Of the remaining 35 deep wells, 7 or 20% contained relatively low fecal coliform concentrations (<15 cfu/100ml). The 18 private wells surveyed were nearly twice as likely (39%) to be contaminated (Table 6.8).

Table 6.8: Wells with fecal coliform contamination in Lumbini, Nepal (2002)

Well Type	Ave Depth [ft]	Ave Age [yrs]	# Wells Tested	% Positive
Private	80	9	18	39%
Open	30	40	1	100%
Public	190	2	35	20%
All Wells	152	5	54	28%

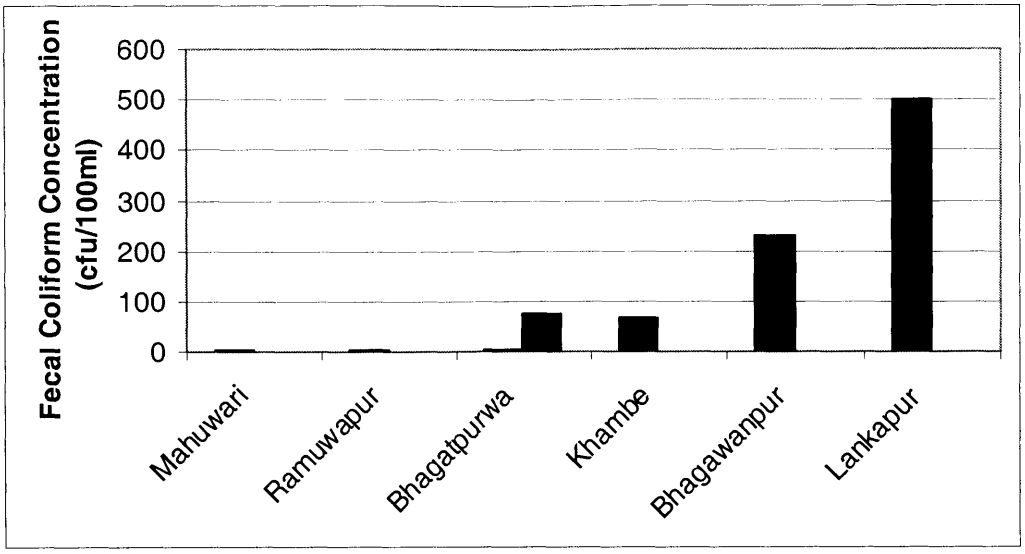
As before with the H_2S testing, these fecal coliform data are good indicators of villages most likely to harbor waterborne pathogens. In addition, enumeration can distinguish between low-level and high-level contamination. There are a total of 7 public wells (out of the 35 deep wells tested) that are contaminated with fecal coliform contamination in the three villages shown in Figure 6.1. Note that each bar represents one contaminated well.

Figure 6.1: Seven public village wells contaminated with fecal coliform bacteria (2002)



While private wells in Mahuwari and Ramuwapur are similar in fecal coliform concentration to that found in public wells (1 to 14 cfu/10ml), Bhagatpurwa, Khambe, Bhagawanpur, and Lankapur have concentrations a magnitude or two greater (i.e. fecal coliform counts in the range of 74 to 500 cfu/100ml) Levels of private well contamination are shown in Figure 6.2. Note that each bar represents one contaminated well.

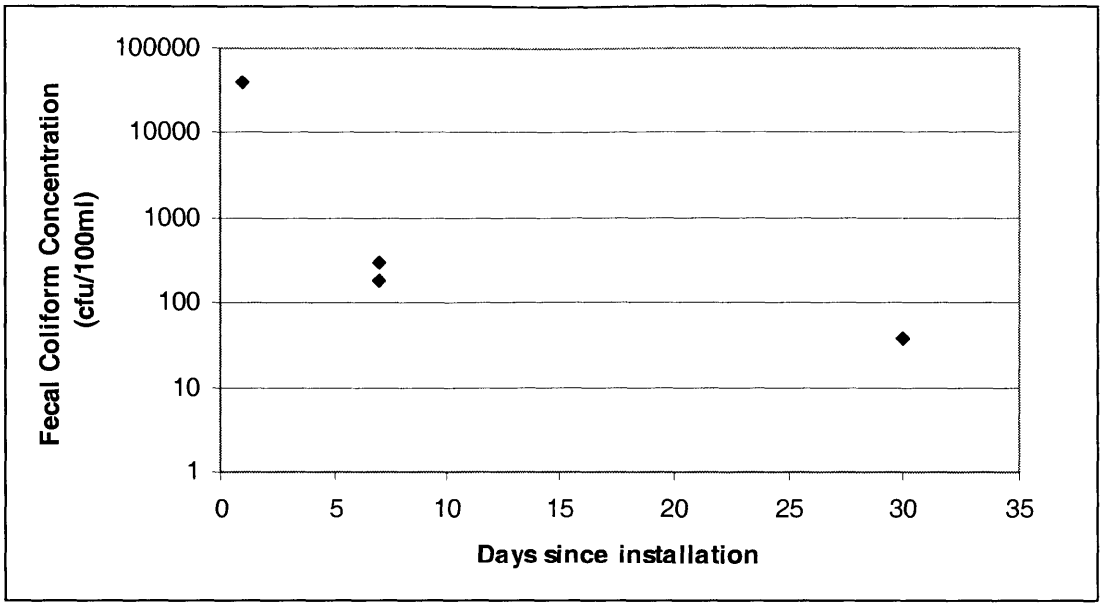
Figure 6.2: Seven private village wells contaminated with fecal coliform bacteria (2002)



6.2.2.3 New well contamination

New wells in the Lumbini area have by far the largest concentrations of fecal coliform bacteria with the highest concentrations detected exceeding 10,000 cfu/100ml for a well sampled the day following installation. New wells (1 day to 1 month old) in Mahuwari, Bhagatpurwa, and Sujandihawa all showed significant fecal contamination ranging from 38 cfu/100ml to 40,000 cfu/100ml. The presence of fecal coliform in new wells is not unexpected due to the standard practice of using cow dung slurry during well drilling. Unknown, however, is the persistence of such contamination in wells following installation. Nine-month-old wells were the youngest in the 2002 data set to test clean. These findings indicate the need for either shock chlorination of new wells or the use of an alternative to cow dung slurry during drilling. For further discussion on this point see Gao (2002) or Sullivan (2002). Figure 6.3 shows fecal coliform concentration in wells as a function of well age. The highest public well concentration other than these new wells was 14 cfu/100ml found in a 3-year-old Ramuwapur well.

Figure 6.3: Contamination of new wells in Lumbini villages



6.2.2.4 H_2S bacteria - fecal coliform test correlations

While H_2S bacteria tests are not yet recognized by standard methods, researchers at the World Health Organization, IDRC, and other institutions have demonstrated H_2S test agreement with coliform bacteria tests (Manja, 1982). During the January 2002 field study in Lumbini, Nepal, H_2S and coliform bacteria tests were highly correlated. Table 6.9 demonstrates the variation in this correlation for samples of different fecal coliform concentration. While very good for detecting all fecal coliform contamination greater than 15 cfu/100ml, drawbacks of H_2S tests are their inability to distinguish clean wells from those minimally contaminated and to separate mid-level contamination (20 cfu/100ml) from high-level contamination (>200cfu/100ml).

Table 6.9: Correlation between IDRC H_2S P/A tests and fecal coliform MF tests*

Level of Fecal Coliform Contamination	Correlation
All levels	0.57
0 cfu/ 100ml	0.82
1-4 cfu/100 ml	0.54
>5 cfu/ 100ml	0.88
>15 cfu/ 100ml	1.0

*Data analysis adapted from Sullivan (2002)

6.3 Biosand in Nepal

Transferred from Samaritan's Purse to a local NGO, Hope for the Nations Nepal, the Biosand filter technology was brought to Nepal in 1998. Hope for the Nations Nepal then constructed and distributed fifteen Biosand filters to homes in the Palpa region near Tansen, and began selling Biosand filters in the Nawalparasi region of the Terai near Naranghat (Paytner, 2001). Since then, over 200 filters have been built and installed in the Nawalparasi district by Durga Ale who was trained by a representative of Samaritan's Purse.[32]

6.3.1 MIT Biosand work 2001

In 2001, MIT Masters of Engineering students, Tse Luen Lee and Nathaniel Paynter traveled to the Nawalparasi and Palpa regions of Nepal to study the technical performance and social acceptability of already installed Biosand filters.[33] 30 filters tested were located in Nawalparasi along the East-West main highway while the 7-8 filters were in remote households outside Tansen in the Palpa District. (Paynter, 2001) Respondents to Paynter's survey reported liking the Biosand filter's high flow rate, improved water taste, and cooling effect of filtration on the water. Lee (2001) and Paynter (2001) concluded the following in regard to the Biosand filter:

- Effectively removes microbial contamination when it is functioning properly
- Religiously and culturally acceptable
- Does not place additional burdens on families
- Easily understood and maintained by Nepali users, although many of them have not been trained in the use of the Biosand filter
- At $27-$35, too expensive for general Nepali population
- Questionable capacity to handle elevated turbidity of rainy season[34]

6.3.2 Demand in Lumbini for point-of-use water treatment

As demonstrated in the Lumbini well surveys, prevalent low-level contamination exists in deep wells and certain private wells contain very high concentrations of fecal coliform. This contamination is occurring even during the dry season when wells are observed to be less turbid and predicted to be less contaminated than during the monsoon season. More importantly, Dr. Mallik of the International Buddhist Society has observed high incidence of waterborne disease among villagers. Of those visiting the IBS health clinic[35] during the month of September 2001 from the 17 IBS villages, 5% show symptoms of

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[32] Durga Ale is one of 4 Biosand filter trainees in Nepal who were trained by Samaritan's Purse. Arjun Chettri of Hope for the Nations, Nepal translated for the course. Of the original 4, 2 failed the course and 1 modified the design resulting in filters that were unsatisfactory to customers (Ale, 2002).

[33] At the time of the January 2001 MIT Nepal Water Project field season, there were about 115 Biosand filters in the Palpa and Nawalparasi Districts of Nepal.

[34] Respondents to Paynter's (2001) survey indicated the need for frequent cleaning during the rainy season.

[35] The women motivator's are also responsible for taking health survey's in the villages and reporting data to Dr. Mallik. These data are a combination of those visiting the health clinic and women motivator reports.

diarrhoea and 13% of Amoebiosis (Table 6.9). In addition, water- washed diseases are common due to water scarcity, lack of privacy, contaminated water, or other issues that may prohibit basic hygienic practice (IBS, 2001).

Table 6.10: Incidence of waterborne disease per 1000 people in September 2001 (IBS, 2001)

Village	Population	Diarrhoea	Amoebiosis
1 Lankapur	157	51	140
2 Mahuwari	644	47	110
3 Khambe	445	157	92
4 Laximapur	382	52	102
5 Mahilwari	730	148	138
6 Dhodahawa	544	6	232
7 Sujandihawa	896	20	127
8 Ramuwapur - Ten	595	42	166
9 Sonbarshi	251	48	159
10 Ramuwapur - Khu	373	38	214
11 Sonbarsha	804	57	83
12 Bhagatpurwa	310	65	145
13 Shivagadiya	426	16	131
14 Sekhuwadand	213	70	197
15 Mujahana	689	116	136
16 Bhagawanpur	975	0	107
17 Lamtihawa	893	8	75
Total	9327	483	1208
% of Population Affected		5%	13%

6.3.3 2002 Biosand filter pilot project

Lumbini area villages are a good location for a Biosand Pilot Project for the following reasons:

- Observed success of Biosand programs in Palpa and Nawalparasi Districts of Nepal (Lee, 2001; Paynter, 2001)
- Existing organizational structure and health focus of IBS village outreach programs including women motivators who could train villagers in filter use, maintenance, and provide regular monitoring
- Microbial well contamination
- Possible recontamination in households
- High incidence of waterborne disease (specifically amoebiosis)[36]
- Turbid well water[37]

[36] The Biosand filter removes 100% of Amoebas by physical-chemical means (ie. No biological growth is necessary). In addition, dysentery can be of bacterial or amoebic origin. It is quite possible that the majority of ill health effects can be attributed to these protozoan and not bacteria.

[37] Peter Moulten's study concluded well water to be too turbid for SODIS and too variable for other means of disinfection. When wells have contamination that ranges from 1 cfu/100ml to >500cfu/100ml, it becomes difficult to designate a specific dose of chlorination. (See Sullivan, 2002 for more information.)

With the above-stated factors in mind, in November 2001, Susan Murcott and Lee Hersh donated funds for the construction of 12 Biosand filters and their distribution to 5 IBS villages during the first week of January 2002. Arjun Chetrri of Hope for the Nations, Nepal received the payment for the filters and paid Durga Ale of Nawalparasi 2000 rupees (US$27) per filter to construct the filters. Filters were constructed and sand sifted in Ale's workshop in Nawalparasi. The concrete part of the filter was first transported to the villages and filters were commissioned when the sand arrived. Because farmland and footpaths are often all that connects villages, some filters had to be transported to villages via tractor.

Table 6.11: Date of installation, location, and flow rate of Biosand filters in Lumbini (2002)

	Village	Owner	Date installed	Flowrate [L/hr]
1	Ramuwapur - Ten	Keshav Pari Yadar	1/6/02	31
2	Ramuwapur - Ten	School	1/6/02	23
3	Sonbarsha	School	1/6/02	34
4	Sonbarsha	Rudra Nath Chavdhay	post 1/19/02	N/A
5	Sekhuwadand	N/A	1/3/02	20
6	Sekhuwadand	N/A	1/3/02	11
7	Khambe	N/A	1/4/02	20
8	Khambe	Devendra Tripoam	1/4/02	23
9	Lumbini	IBS kitchen	1/02	N/A
10	Lumbini	Hotel near IBS	1/02	N/A
11	Mujuhana*	School	post 1/19/02	N/A
12	Madubani	N/A	N/A	N/A

*Filter 11 was to be moved from IBS to Mujuhana School during January 2002.

6.3.4 Biosand results

Flow rate

Since flow rate is a critical design parameter of the Biosand filter, the author measured Biosand filter flow rates within the first week of their installation during January 6-11, 2002. Table 6.11 shows the range of flow rates observed, and the marked reduction in flow rate following their first 5-7 days of operation. A filter in Sekhuwadand had a very slow flow rate of 11L/hr.

Table 6.12: Biosand Filter Flow rates (2002)

All	23
New filters	29
5-7 day old filters	18

Lee (2001) reported an average flow rate of 30L/hr and a range of 4L/hr to 60L/hr in the 39 filters he tested, all of which had been in use for an extended period of time (approximately 1 year). Slow flow rates could result from highly turbid source water, insufficient washing of the sand, or lack of user education. One filter located in a private residence was used continuously following its installation with 15 buckets of 20L each

poured into the filter the first day. Approximating 15 buckets of 20L each in 10 hours gives an average flow rate of 25 L/hr for the first day. Flow rate then dropped to ~3L/hr (enough to filter 40L/ day) and held steady for the next 4 days until it was cleaned, when filter was revicited.

Fecal coliform results

Similar to all slow sand filters regardless of size, it takes time for the *schmutzdecke* and biofilm to form at the sand-water interface of the Biosand filter following installation and cleaning. While it was valuable to observe the installation and commissioning of new Biosand filters, the author of this thesis was present in Lumbini for only 12 days during the commissioning of the Biosand filters. Therefore, the filters were not "ready" to be tested for water treatment efficiency. The effluent of 5 filters and their source water were tested for fecal coliform within a week following their installation and, thus, the results are inconclusive. Most households reported using private well water in their filter whereas before some would carry drinking water from a public well. While, in general, public wells are much cleaner than private wells, the 5 private wells whose water fed Biosand filters contained little contamination (only one well had fecal coliform counts >2cfu/100ml). While well contamination likely accounts for a portion of observed health effects, contamination within the household is also quite possible. Water flowing from one Biosand filter spout in Sekhuwadand contained a fecal coliform concentration of 2 cfu/100ml as compared to the 10 cfu/100ml in bucket below.

Field observations

The Biosand Filter Pilot Project marks the first introduction of the Biosand filter technology to villages in the Lumbini district. 12 Biosand filters were installed in 5 different IBS villages with 2 at IBS itself.[38] Most filters were installed in the homes of prominent village members or in local schools by Durga Ale of the Nawalparasi District with the assistance of an IBS employee. Supervised by Arjun Chettri of Hope for the Nations, Nepal and the author, the same IBS employee installed 3 remaining filters on January 6, 2002. Due to a missing diffuser plate, one filter in Sonbarsha was not installed.

Durga Ale sifted and washed the filter media in his Nawalparasi workshop prior to filter installation. Ale's method of preparation is unknown at this time. Prepackaged filter media was, then, transported to villages where the concrete filters were already located. The author did not observe the transport of the concrete filters. Several men, together, were able to move the concrete filters to a convenient place where the media could be poured. Following correct protocol as observed by the author, the bottom half of the filter was filled with water and ~5cm of underdrain gravel was added to the water followed by approximately 5cm of support gravel and the correct amount of sand filter media.[39] More water was added when necessary, and media was always poured into the water. During field installation, the men installing filters gave male filter owners a brief tutorial on filter

[38] One of the two filters at IBS during January 2002 is supposed to be installed in Mujahana School. The only problem is that its sand and water have already been poured.

[39] The filters installed at the Ramuwapur School and at a private residence in Ramuwapur were both missing a few centimeters of sand.

operation. Water was poured into the filter to demonstrate its purification ability, and villagers were told of the benefits of drinking filtered water (Chettri, 2002).

The author also vicited filters 5-7 days following their installation. In these cases, gender separation in knowledge of basic maintenance seemed prevalent with many women not understanding how to perform cleaning. It was common for women to say, "my husband knows, but he is not here." Villagers expressed interest in learning more about filter cleaning and operation. In one village vicited by the author, the flow of a new Biosand filter greatly declined over a short period of time due to nearly contiuous use since its installation. When questioned about why so much water had been poured into the filter and if he understood how to perform cleaning, the filter owner expressed great interest in learning. In fact, he said (through various translations), " Just tell us how to clean it, use it, maintain it, and we will."

Discussion

Much can be learned from the initial evaluation of the Biosand Filter Pilot Project. For the most part, filters were built and installed according to procedures taught to Durga Ale and Arjun Chettri by a representative from Samaritan's Purse. While willingness-to-pay or contribute labor was not determined, several different villagers did express interest in having their own Biosand filters in the future. Thus, potential demand for the expansion of the pilot project does exist.

However, those participating in the Lumbini Biosand filter pilot study were not adequately educated in the installation, operation, and maintenance of Biosand filters. Softer principles such as not moving the filter following installation were not understood. This lack of education could be divided into two categories. One is the disparity between what is understood by those who installed the filters and by those implementing the project (MIT or Samaritan's purse), and the other is the lack of user knowledge of the operation and maintenance of filters. While well trained in the procedure of filter installation, the men installing filters had not been properly trained in the essential education that must accompany the actual physical filter. In addition, the existing organization structure of IBS includes women motivators who were, also, not educated in Biosand filter specifics. It is not a question of whether people have the capacity to learn essential Biosand filter principles, it's a question of them being provided the opportunity to learn and the subsequent thoroughness of this education.

7 Conclusions

7.1 Lumbini well survey

While it was demonstrated that H_2S tests are good for ruling out high-level contamination, the benefits of the membrane filtration analysis performed in Lumbini during January 2002 are numerous. Public wells, in general, offer much safer drinking water than private wells with 20% of public wells and 39% of private wells testing positive for fecal coliform bacteria. More importantly, the concentration range of private well fecal coliform bacteria was much greater (1cfu/100ml to 500 cfu/100ml) than that of public wells (1cfu/100ml to 14cfu/100ml). Lankapur, Ramuwapur-Khu, and Khambe all have both fecal coliform and H_2S bacteria in their public wells, and in Lamtihawa 2 of 2 private wells tested negative for H_2S bacteria while 2 of 4 public wells were positive. Dhodahawa has deep public wells that have tested positive for H_2S during January of the past three years (2000-2002) indicating a long-term contamination source.

It was found that cow dung slurry used during well drilling causes contamination that persists for at least a month with fecal coliform concentrations range from 40,000 cfu/100ml the day following installation to ~38 cfu/100ml a month later. Furthermore, all fecal coliform from cow dung slurry source disappears within 9 months of installation.

An important conclusion from this work is that contamination does exist in the Lumbini area and that wells need to be tested during summer months to eliminate the seasonal bias of the existing data set. When considering new interventions or well survey extensions, those villages with the highest incidence of waterborne disease should be targeted. In addition, special attention should be paid to the villages of Lankapur, Ramuwapur-Khu, Khambe, Dhodahawa, and Lamtihawa, as their deep public tubewells may be a threat to human health.

7.2 Lumbini Biosand Filter Pilot Project

Durga Ale built 12 concrete filters for the Lumbini Biosand Pilot Project, but prepared the associated media in the Nawalparasi District of Nepal. These filters and their media were then transported to 5 Lumbini District villages where they were installed by either an IBS employee or Durga Ale, himself. While installation procedures were technically sound, the importance of protecting the biofilm and *schmutzdecke* did not seem to be understood. While filter users were provided with some form of education, they did not understand basic filter operation and maintenance essentials including cleaning. In addition, flow rates dropped sharply following installation, which suggests a problem with the sand source or sand preparation procedure. Those who own filters expressed a desire to become educated about their filters while other villagers were interested in having filters of their own.

7.3 Recommendations

Expanding the Lumbini Biosand pilot project offers opportunity to refine the existing Biosand construction, distribution, and education process. Various modifications to building and filter installation explained in Chapter 4 could be easily applied in the case of Lumbini and can be summarized in the following four key points:

- Improvement of sand preparation
  - Testing of different sand sources for microbial contamination
  - Buying sand in bulk[40]
  - Modification of sieving
- Involve community in sieving and washing
- Disinfect standpipe of filter during installation using liquid chlorine solution
- Flushing filters with ~100L of water following installation and cleaning

Necessary to the successful implementation of Biosand filters, filter users should be educated not only in basic filter operation but also in basic filter maintenance. Simply warning users of potential problems before they occur can solve many potential filter problems. This education should include how to clean the filter when necessary, how to prevent filter clogging, the importance of not moving the filter following installation, and the importance of keeping the diffuser basin in place. In areas serviced by a distribution system, users should be discouraged from attaching a constant water source to the inlet or a tube from the outlet. To best transfer this knowledge in the case of Lumbini, women motivators and other community educators should, themselves, become educated. This can be accomplished through hands-on training sessions and the preparation and translation of educational material such as a Biosand filter users guide into Nepali. This educational material could be based on the 8 key educational points described in Chapter 4.

Following the commission and initial education described above, continuing education and connection to the filters should be established. Since essentially no structural filter maintenance or new parts are required, continuing Biosand filter education could be easily incorporated into the existing health education programs provided by the women motivators. This would be a natural extension of their current role and would include motivating villagers to continue to use the deep public tubewells (which they already do), reminding users of the 8 key educational points for Biosand success, and possibly cleaning taps monthly with diluted bleach or Piyush solution (if deemed necessary). Any questions that may arise during village visits could be answered by a support structure at IBS. Much like the Lumbini Chlorination Pilot Study, involving women motivators will automatically result in the inclusion of village women in Biosand filter operation.

If the Biosand pilot project is to be expanded to many more houses, someone within villages could be designated to be in charge of filter maintenance if any issues or questions were to arise. This could be done within the existing organizational structure of

[40] Maitri (2002) indicated that buying sand by the truckload and having it delivered directly to IBS could save substantial money.

each village and could be based on the willingness and availability of someone to do such work. In addition to continuing education, filter performance should be periodically evaluated based upon definable parameters including removal efficiency of indicator organisms and flow rate. The key to successful program monitoring is in establishing standard testing protocols for sample collection and analysis. By carefully recording the performance of specific filters, variation in filter performance can be best evaluated and problems can be isolated.

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Appendix A
Nepal Packing List

Quantity	Item	Company	Catalog #	Unit Price
	Membrane Filtration:			
1	Filter Assembly Holder (2nd hand)	Millipore	XX6300120	$600.00
1	Tube to connect Filter Assembly Holder	Millipore	XX6504710	$21.00
1	Nalgene Hand pump (P1287)	VWR	6131-0020	$67.54
450	47 mm filter papers	Millipore	HAWG047S1	$0.19
500	petri dishes with pads	Millipore	PD10047S5	$0.27
1	Forceps	x	x	x
	Nutrient Broth & Preservation:			
150	m-Endo total coliform broth	Millipore	M00000P-2E	$1.00
150	m-FC w/ rosilic acid (fecal coliform) broth	Millipore	M00000P-2F	$1.00
15	P/A Broth w/ MUG Ampules	HACH	24955-25	x
1	EC Medium - 100 g (powder)	BD/Difco	DF0314-15	$1.00
1	Bacto EC Medium w/Mug - 100 g (powder)	BD/Difco	DF0022-15	$79.75
1	Travel bag and ice packs to transport	x	x	x
1	UV lamp	HACH	24152-00	$12.50
10	AA batteries (4 for UV lamp + 6 spare)	x	x	x
1	Cooler/ refridgerator for storage	x	x	x
	Incubator:			
1	Single Chamber Incubator (230V)	Millipore	XX631K230	$750
1	Power supply for incubators (adaptor 230V)	Millipore	--	$100
3	Nickel Cadmium Battery	Millipore	XX6320022	$185
1	Red-filled VWR Thermometer (35 - 50 C)	VWR	61067-855	$8.41
2	Battery charger (230V)	Millipore	XX6320022	$75.00
	Steralization:			
1	Methanol - 4 L	x	x	x
2	Lighter	x	x	x
4	Germicidal clothes for disinfecting test surfaces			
1	Large container to hold batch sterilyzed water	x	x	x
2	Squeeze bottles (for Methanol and sterilyzed water)	Nalgene	x	x
1	Stove, Pot w/ lid, Gas to sterilyze glass ware	x	x	x
2	Hand sanitizer	x	x	x
	Dilutions:			
1	Automatic pipette, autoclavable 1-5 ml	Oxford	53502-440	$153.83
100	Pipette tips (glass or plastic)	VWR	53503-826	$0.10
8	Glass 100ml bottles	VWR	15507-164	$3.77
2	graduated cylinder, polyp-100 ml	VWR	24776-086	$8.65
	Turbidity:			
1	Pocket Turbidimeters	HACH	52600-00	$470.00
10	AAA Batteries for turbidimeter	x	x	x
	Sample collection:			
1	Metal stirrer	x	x	x
1	Thermometer to measure water temperature	x	x	x
1	Container to measure flow rate	x	x	x
3	Whirlpack bags - 100 ml - 100/pk	VWR	11216-780	$13.94

Appendix B

Private wells tested during January 2002 in Lumbini district

			Membrane Filtration		H_2S Tests	
Well	Depth	Age	Fecal Coliform [cfu/100ml]	E.Coli *[cfu/100ml]*	IDRC	HACH
L3			0	0		
K5	30	20	66	36		
K8		4			N	
K10	30	8			P	
K11	20	25			N	
B12	125	2			N	N
B17				0	N	N
B20			230	20	P	
SW1	60	6	0		N	N
SW4	60	4	0		N	
SW6			0		P	P
SW8	65	1	0		N	N
DW10	25	15	0		P	P
SONW3	30	2	0		N	
SONW4			0		N	
RAMW6			2		N	
MUH2	40	25	1		N	
BHA12	90	22	74		P	
BHA16	95	2	4		N	
RAM2	132	1	0	0	P	N
LNK6	35	12	0	12	P	P
LNK7	30	10	>500	>500	P	P
HOTEL	200	7	0	0	N	
MAHW3	40	10			N	P
MAHW5	35	4			P	P
MAHW7	40	10			P	P

Appendix B (cont.)

Private wells tested during January 2002 in Lumbini district

Well	Date Visited	Village	Owner
L3	1/8/2002	Lamtihawa	
K5	1/9/2002	Kambe	Devendra Tripuam
K8	1/9/2002	Kambe	Satendra Tripuam
K10	1/9/2002	Kambe	Chlorination Household
K11	1/9/2002	Kambe	Balibadra Nath Tiwari
B12	1/9/2002	Bhagawanpur	School Well
B17	1/9/2002	Bhagawanpur	Chlorination Household
B20	1/9/2002	Bhagawanpur	Chlorination Household
SW1	1/10/2002	Sekhuwadan	
SW4	1/10/2002	Sekhuwadan	
SW6	1/10/2002	Sekhuwadan	
SW8	1/10/2002	Sekhuwadan	Indra loadh
DW10	1/10/2002	Dhodahawa	Shoeepath Lohar
SONW3	1/11/2002	Sonbarsha	Rojan Dhuniya
SONW4	1/11/2002	Sonbarsha	Buddha Fakir
RAMW6	1/11/2002	Ramuwapur	
MUH2	1/13/2002	Muhuwari	Shiva Shanhar Tiwari
BHA12	1/13/2002	Bhagatpurwa	Sitaram Yadav
BHA16	1/13/2002	Bhagatpurwa	
RAM2	1/14/2002	Ramuwapur	Chingut Harijau
LNK6	1/14/2002	Lankapur	Buddhu
LNK7	1/14/2002	Lankapur	Tamueswos Lodh
HOTEL	1/14/2002		Hotel
MAHW3	1/17/2002	Mahilwari	Ompoakas Kiwori
MAHW5	1/17/2002	Mahilwari	Ramanand
MAHW7	1/17/2002	Mahilwari	Ompoakas Baniya

Appendix B (cont.): Public wells tested in Lumbini District (Jan 2002)

Well	Date Visited	Village	Depth	Age
L1	1/8/2002	Lamtihawa	200	1
M3	1/8/2002	Mujahana	230	3
L2	1/8/2002	Lamtihawa	180	2
B13	1/9/2002	Bhagawanpur	195	1
B14	1/9/2002	Bhagawanpur	200	3
B15	1/9/2002	Bhagawanpur	230	3
B16	1/9/2002	Bhagawanpur	190	3
DW9	1/10/2002	Dhodahawa	350	3
DW11	1/10/2002	Dhodahawa	200	3
SONW1	1/11/2002	Sonbarsha	210	0.5
SONW2	1/11/2002	Sonbarsha	195	2
RAMW5	1/11/2002	Ramuwapur	185	2
RAMW8	1/11/2002	Ramuwapur		
RAMW9	1/11/2002	Ramuwapur		
SHIW11	1/11/2002	Sonbarshi	190	5
SHIW12	1/11/2002	Sonbarshi	190	5
SHIW13	1/11/2002	Sonbarshi	190	5
MUH4	1/13/2002	Muhuwari	195	1 week
MUH5	1/13/2002	Muhuwari	191	1 week
MUH6	1/13/2002	Muhuwari	150	2
MUH7	1/13/2002	Muhuwari	195	2
MUH8	1/13/2002	Muhuwari	203	2
BHA9	1/13/2002	Bhagatpurwa	225	1 day
BHA10	1/13/2002	Bhagatpurwa	110	0.5
BHA11	1/13/2002	Bhagatpurwa	110	0.5
BHA13	1/13/2002	Bhagatpurwa	225	0.5
BHA14	1/13/2002	Bhagatpurwa	110	2
SVG17	1/13/2002	Shivagadawa	74	2
SVG18	1/13/2002	Shivagadawa	170	2
RAM1	1/14/2002	Ramuwapur	190	3
LNK3	1/14/2002	Lankapur	180	2
LNK4	1/14/2002	Lankapur	180	4 to 5
LNK5	1/14/2002	Lankapur	180	12
LNK8	1/14/2002	Lankapur		
LNK9	1/14/2002	Lankapur		1
SUJ10	1/14/2002	Sujandihawa	200	9 months
SUJ11	1/14/2002	Sujandihawa	160	3
SUJ12	1/14/2002	Sujandihawa	195	1 month
SUJ13	1/14/2002	Sujandihawa	195	9 months
MAHW1	1/17/2002	Mahilwari	187	2
MAHW2	1/17/2002	Mahilwari	190	1
MAHW4	1/17/2002	Mahilwari	190	1
LAXW1	1/18/2002	Laximapur	195	2
LAXW2	1/18/2002	Laximapur	180	1
LAXW3	1/18/2002	Laximapur	185	1
LAXW4	1/18/2002	Laximapur	120	4
LAXW5	1/18/2002	Laximapur	185	15 Days
K1	1/9/2002	Kambe	190	3
K4	1/9/2002	Kambe	190	1

Appendix B (cont.) Public wells tested in Lumbini District (January 2002)

Well	Fecal Coliform [cfu/100ml]	E.Coli *[cfu/100ml]*	IDRC	HACH
L1	0	0		
M3	0	0		
L2	0	0		
B13			N	N
B14			N	
B15	0		N	N
B16	0		N	
DW9	0		N	N
DW11	0		P	P
SONW1	0		P	P
SONW2	0		N	N
RAMW5	6		P	P
RAMW8	4		N	
RAMW9	0		N	N
SHIW11	0		N	N
SHIW12	0		N	N
SHIW13	0		N	
MUH4	187		P	
MUH5	>300		P	
MUH6	0		N	
MUH7	0		N	
MUH8	0		N	
BHA9	~40000		P	
BHA10	0		N	
BHA11	0		N	
BHA13	0		N	
BHA14	0		N	
SVG17	0		N	
SVG18	0		N	
RAM1	14	19	N	N
LNK3	0	0	N	N
LNK4	4	11	P	P
LNK5	0	12	N	P
LNK8	0	0	N	N
LNK9	2	0	P	P
SUJ10	0	0	N	N
SUJ11	0	2	N	N
SUJ12	38	52	P	P
SUJ13	0	0	N	N
MAHW1			N	N
MAHW2			P	P
MAHW4			N	N
LAXW1			P	
LAXW2			N	
LAXW3			P	
LAXW4			P	
LAXW5			P	
K1	2		N	N
K4	2		P	P